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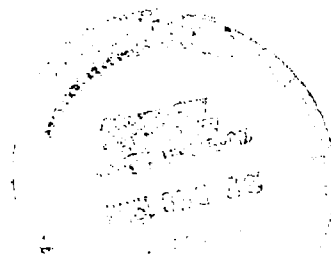


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SIMULATION STUDIES OF THE SUPERSONIC TRANSPORT IN FUTURE AIR TRAFFIC CONTROL SYSTEMS

*by Richard H. Sawyer, Norman S. Silsby,
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SUMMARY

The problems anticipated for the supersonic transport (SST) in operations in simulated Air Traffic Control (ATC) systems conceived for the time period for the introduction of the SST into service have been studied. The studies were made in real time by using an SST aircraft flight simulator and the Federal Aviation Administration (FAA) ATC simulation facilities. Airline crews operated the SST flight simulator, and experienced air-traffic controllers operated the ATC simulation facilities. Design-study configurations of the SST were used in the tests. The test program consisted of departures and arrivals under weather conditions which required operations by FAA Instrument Flight Rules in the New York, Los Angeles, San Francisco, and London terminal areas.

The investigation showed that for the future ATC system concepts investigated, substantial changes in course (up to nearly 50°) at supersonic speeds were required in many instances on the airway routes and to effect transition to and from the high-altitude track systems. Such changes in course at supersonic speeds were detrimental to SST performance and increased the workload for the crew. Further, substantial amounts of maneuver fuel were required for complying with ATC flight-path restrictions and for following indirect routings along the airways and to and from the high-altitude track systems. On a mission basis, the calculated total fuel requirements on the average were found to exceed the mission fuel requirements provided under the Tentative Airworthiness Standards for Supersonic Transports (Nov. 1, 1965; Revision 4, Dec. 29, 1967) by from about 6 to 7.5 percent of mission fuel for the transatlantic mission and from about 2 to 6.5 percent of mission fuel for the transcontinental mission. Corresponding maneuver times were found to increase mission block times on the average from about 17 to 18 minutes for the transatlantic missions and from 5 to 11 minutes for the transcontinental missions. The time spent in climbing and descending turns in the departure and arrival operations in the New York area was, on the average, of the same order or greater than that found in previous tests in the present-day ATC system. For the same operations, the time spent on ATC communications was on the average about the same as that found in the tests in the present-day ATC system.

INTRODUCTION

The need of planning for the introduction of the supersonic transport (SST) into the Air Traffic Control (ATC) system was recognized early by the National Aeronautics and Space Administration (NASA) and the Federal Aviation Administration (FAA). In recognition of this need, preliminary ATC simulation studies (ref. 1) were made by the FAA (1963) and an exploratory flight evaluation of a high performance military airplane (ref. 2) was made by the NASA (1964).

In order to study the problems connected with the integration of the SST into the ATC system in more depth, the NASA and FAA have also jointly conducted a program using the ATC simulation facilities of FAA located at the National Aviation Facilities Experimental Center, Atlantic City, New Jersey, and an NASA fixed-base SST simulator located at the Langley Research Center, Hampton, Virginia. The joining of these facilities by telephone data lines provided a research method by which proposed designs of the SST could be studied in simulated real-time ATC environments. Airline crews were used in the SST simulator, which provided a realistic flight-compartment environment. Experienced air-traffic controllers manned the ATC simulator.

In the initial SST ATC program, simulated operations of the SST were conducted in the present ATC system. From these tests, the effects of the SST on the ATC system were reported by the FAA in reference 3, and the effects of the ATC system on the SST were reported by the NASA in reference 4.

In the present program, simulated operations of the SST were conducted in future ATC systems conceived by the FAA for the 1970-1975 time period. The future systems basically differed from the present-day system in providing high-altitude track systems for supersonic flight and in providing the air-traffic controllers with a semiautomated flight-data display system. The FAA results from the present program were reported in references 5 and 6; and the NASA results are given herein.

SYMBOLS

M	Mach number
M_{MO}	maximum-operating-limit Mach number
Δp	sonic-boom overpressure level, pounds force per square foot (newtons per square meter)
$(T/W)_{TO}$	ratio of thrust to weight at take-off

V_{MO}	maximum-operating-limit airspeed, knots
x	east-west ground coordinate, nautical miles
y	north-south ground coordinate, nautical miles
z	altitude, feet (kilometers)

ABBREVIATIONS

ARTCC	Air Route Traffic Control Center
ATC	Air Traffic Control
ATIS	Automatic Terminal Information Service
DME	distance-measuring equipment
FAA	Federal Aviation Administration
FL	flight level (pressure altitude in hundreds of feet)
IFR	Instrument Flight Rules
ILS	instrument landing system
JFK	John F. Kennedy International Airport
KLAS	knots indicated airspeed
LAX	Los Angeles International Airport
LON	London International Airport (Heathrow)
LRC	Langley Research Center (NASA)
NAFEC	National Aviation Facilities Experimental Center (FAA)
SFO	San Francisco International Airport

SID	standard instrument departure
SST	supersonic transport
VHF	very high frequency
VOR	VHF omnirange radio navigation station
VORTAC	VOR station with DME provision

EQUIPMENT

A block diagram of the equipment used in this study, together with the interconnections of this equipment, is given in figure 1. At the NASA Langley Research Center, an aircraft flight simulator linked to the analog-computer facility was used to represent the SST design being investigated. This equipment was connected to the FAA ATC simulator at NAFEC in Atlantic City, New Jersey, by means of data and voice lines.

SST Simulator

The flight compartment of the fixed-base aircraft flight simulator used to represent the SST was similar to that of a current jet-transport airplane (fig. 2). The basic flight instrumentation (fig. 3) included displays having various combinations of drum, counter, and pointer indicators; a moving-tape display; a vertical-scale moving pointer display; and a modern flight director system. The flight instrumentation also included an optical-projector type of pictorial navigation display located in the center of the flight-instrumentation panel. A photograph of the pictorial navigation display with a terminal area map positioned over the screen to represent the view as seen by the pilot is shown as figure 4. Features of the display include choice of either en route or terminal area maps. The en route map had a scale of 10 nautical miles per inch (3.94 n. mi. per cm); the terminal area map had a scale of 5 nautical miles per inch (1.97 n. mi. per cm). A more complete description of the pictorial navigation display is included in reference 7.

The characteristics of the SST under study were programed on five analog computers. Equations for six degrees of freedom were used in the representation of the airplane motions. The characteristics of the engines and other airplane systems were also programed in the computer.

The SST simulator also included accessory equipment for navigation, communication, and data-transmission requirements. The radio-aids equipment provided simulation of VORTAC stations, marker beacons, and ILS stations. The communications

equipment simulated VHF radio communications between the pilots and the air-traffic controllers over the telephone lines. A tape recorder was used to preserve pilot—air-traffic-controller conversations. Two 30- by 30-inch (76.2- by 76.2-cm) x-y plotters were used to record the ground track — one on a terminal map (120 n. mi. by 120 n. mi.), the other on an en route area map (either 400 n. mi. by 400 n. mi. or 800 n. mi. by 800 n. mi.).

ATC Simulator

The real-time simulated ATC environment was created by means of a combination of ATC facilities simulation and an air-traffic simulation. Both simulations were provided by the FAA and created the environment in which the SST simulator was operated for the tests.

The ATC facilities simulation consisted of entire and partial Air Route Traffic Control Centers (ARTCC), as required, and an Approach Control and Tower Complex for one airport. These facilities were staffed by experienced air-traffic controllers. Each controller was provided with modern display and communication equipment, including display of airplane target symbols and target identification and altitude tags (alpha-numeric displays) on 19-inch (48.3-cm) scan-converted bright cathode-ray tubes. (See fig. 5.) Controllers were also provided with flight-path-extrapolation capability (based on projection of current airplane performance) up to 8 minutes for each target symbol and capability of blinking a target symbol as an attention device for handoff (transfer of a target to another controller).

The air-traffic sample simulation was created by 108 electronic radar target generators (fig. 6), each programed to have the generalized flight characteristics of a particular type of airplane. The traffic sample included propeller, subsonic jet, and SST airplanes. The operator of each target generator simulated horizontal and vertical navigation of the airplane by means of a control panel and a spot of light projected on an airways map at the top of a console. The flight was conducted according to a programed script and instructions from the air-traffic controllers received over a simulated radio-communication network. The x,y position data (ground coordinates) from the target generator were fed through radar simulators that transformed the data into radar form; that is, properly gated target video pulses and antenna position. The video pulse and antenna data were fed to the controllers' displays providing the air-traffic sample.

Data Transmission and Communications

Data transmission between the SST simulator and the ATC simulations facilities was effected over telephone lines. The SST simulator ground coordinates x and y,

altitude z , and radar beacon transponder signal were transmitted via a data telephone line. The SST simulator position and transponder information joined the position information from the target generators for display on the controllers' displays.

Communications between the pilots of the SST simulator and the controllers were effected over two private telephone lines which were connected into a special telephone system used for communications between target-generator pilots and controllers. The special telephone system allowed all pilots to dial the same controller simultaneously; thus, the interference of actual radio communications was simulated. Selection of an assigned frequency on the VHF radio-communications panel in the SST cockpit automatically dialed the line in the special telephone system to the controller with whom communications were desired.

TEST PROGRAM

General

The test program was designed to study, in separate phases, departure and arrival operations under IFR conditions into and out of JFK and LAX. A few special departure and arrival operations were also made with the SST simulator into and out of SFO and LON with effects of traffic conditions on SST operations simulated by use of special controller handling techniques. The test areas for the oceanic and domestic operations at JFK were each 800 by 800 nautical miles; at SFO and LON, 400 by 400 nautical miles; and at LAX 800 by 1500 nautical miles. The test areas and route structures are shown in figure 7. The JFK test environment included the New York ARTCC area, JFK Approach Control and Tower facilities, and portions of the Boston, Cleveland, Chicago, Indianapolis, Washington, Atlanta, and Jacksonville ARTCC areas and the New York Oceanic Control Sectors. The LAX test environment included the Los Angeles ARTCC area, Los Angeles Approach Control and Tower facilities, and portions of the Oakland and Salt Lake City ARTCC areas and the Oakland Oceanic Control Areas. The route structures used, representing FAA concepts for the 1970 period, consisted of the present-day airway structure at the lower altitudes and parallel one-way track systems at the higher altitudes. For the JFK, LON, and SFO environments, the division between the airway structure and track system was set at FL 430; for the LAX environment, the division was set at FL 390.

The traffic samples used at NAFEC included current propeller-driven and subsonic jet airplanes, as well as supersonic airplanes. The SST's represented in these traffic samples were the Anglo-French Concorde design (cruise Mach number of 2.2) and United States design-study configurations (cruise Mach number of 2.7). A United States design-study configuration with a double-delta wing was used in the JFK, SFO, and LON environments, and a United States design-study configuration with a variable-sweep wing was

used in the LAX environment. The United States design-study configuration used in each case was considered to be the optimum design at the time of the tests. The LAX area-traffic samples also included representations of forthcoming large subsonic jet airplanes of the Lockheed C5A and Boeing 747 class and military supersonic airplanes (cruise Mach number of 3.0). The military supersonic airplanes were operated from and into Beale and Edwards Air Force Bases. Air movements of propeller-driven and subsonic jet airplanes were based on peak-hour traffic figures for the area. Movements of other types of airplanes were based on estimated totals for the 1970 time period.

All traffic was under the positive control of an ARTCC or airport departure, arrival, and tower facilities. Ceiling and visibility conditions at the destination airport were assumed equal to the minimum values allowable for landing. The following conditions relative to facilities and equipment were provided or assumed as representative of the 1970-1975 time period:

(1) Surveillance radar coverage existed throughout the areas simulated. Secondary surveillance radar (ATC Radar Beacon System) coverage extended to 400 nautical miles from the departure or arrival airport.

(2) All airplanes were equipped with 4096 code radar-beacon-transponder capability with common (civil and military) ATC identification and automatic altitude-reporting modes.

(3) Airports had parallel, ILS equipped runways permitting simultaneous landings of two airplanes.

(4) Radio-communication equipment provided direct controller-pilot communications throughout the areas simulated. A satellite-communication system allowed assignment of special frequencies for SST's and special military flights during operations above FL 390.

(5) Navigation-equipment accuracy permitted ocean track separation as low as 30 nautical miles for SST airplanes and 90 nautical miles for subsonic airplanes.

(6) Automatic Terminal Information Service (ATIS) was available on navigation-aid frequencies at several stations within a radius of approximately 400 nautical miles from the destination airport.

Characteristics of Airplane Designs Used in SST Simulator

The same two United States SST design-study configurations represented in the traffic samples were used in the SST simulator. Each was designed to have a cruise Mach number of 2.7. Configuration A employed a variable-sweep wing and configuration B employed a fixed double-delta wing. Both configurations used afterburning turbo-jet engines, and both were equipped with forebodies that could be lowered at low speeds for improved visibility from the flight compartment. For each configuration, the

international and domestic versions were based on the same airframe. For configuration A, the same engines were used on both versions; however, for configuration B, the engines were scaled down in the lighter domestic version to retain the same take-off thrust-to-weight ratio as the international version. (See table I.) The minimum transonic acceleration values given in table I are for operations restricted by a sonic-boom overpressure limit of 2.0 pounds force per square foot (95.7 N/m^2) for the domestic versions, 2.5 pounds force per square foot (119.7 N/m^2) for the international version of configuration B, and unrestricted overpressure limit (V_{MO} for climb) for the international version of configuration A. The wing-loading values are for the take-off condition.

TABLE I.- SST CHARACTERISTICS

Configuration	$(T/W)_{TO}$ (*)	Minimum transonic acceleration		Wing loadings	
		ft/sec ²	m/sec ²	lbf/ft ²	kN/m ²
A (variable-sweep wing):					
International	0.27	3.5	1.1	75	3.6
Domestic	.31	1.3	.4	63	3.0
B (fixed double-delta wing):					
International	0.40	2.3	0.7	53	2.5
Domestic	.40	1.6	.5	47	2.2

*For maximum unaugmented condition, configuration A; for maximum augmented condition, configuration B.

For both configurations, the basic airplane damping was augmented about all three axes to provide satisfactory handling qualities. A leading-edge flap was automatically programmed to improve the subsonic lift-drag-ratio characteristics of configuration B.

SST Operating Procedures

The SST simulator was operated by teams each consisting of a captain and a first officer. The crews from Trans World Airlines and United Air Lines included pilots in airline supervisory and management positions as well as those engaged in full-time scheduled airline operations. Airline experience of crew members varied from 8 years (4000 flight hours) to 28 years (22 000 flight hours).

A typical departure operation for the SST simulator was initiated just prior to scheduled departure time by a radio call from the crew to ATC departure control for clearance instructions and ended when cruise conditions had been established. For all departures, take-off was delayed for 60 seconds after take-off clearance was received to simulate the time required for completion of the take-off check list and for taxiing onto the runway. Arrival operations were initiated in cruising flight by a radio call from the crew giving an estimated time of arrival over a prescribed location and ended at touch-down on the runway. For some departures and arrivals, the SST was operated in cruising flight for a brief period by use of either cruise-climb or step-climb procedures.

The climb and descent schedules used and the engine, buffet, structural, and sonic-boom overpressure-limitation boundaries for SST configurations A and B are shown in figures 8 and 9. For each configuration, separate schedule and limitation figures (parts (a) and (b)) are given for oceanic (international version) and domestic operations because of the variation in climb schedules and buffet boundaries associated with weight and allowable sonic-boom overpressure level differences. For oceanic climbs, a sonic-boom overpressure limit of 2.5 pounds force per square foot (119.7 N/m^2) was prescribed, while for overland climb operations, the sonic-boom level was restricted to 2.0 pounds force per square foot (95.7 N/m^2). The thrust and configuration schedules used in the climb and descent operations are given in table II.

TABLE II.- THRUST AND CONFIGURATION SCHEDULES

Flight condition	Configuration A				Configuration B	
	Thrust level	Flap position		Forebody position	Thrust level	Forebody position
		Inboard, deg	Outboard, deg			
Take-off	Maximum unaugmented	20	40	Down	Maximum augmented	Down
Noise abatement	75 percent maximum rpm	5	5	Down	Minimum augmented	Down
Subsonic climb	Maximum unaugmented	0	0	Up at $M = 0.85$	Minimum augmented	Up by 250 KIAS
Supersonic climb	Maximum augmented	0	0	Up	Maximum augmented	Up
Supersonic descent	Flight idle	0	0	Up	Flight idle	Up
Subsonic descent	Flight idle	0	0	Down at $M = 0.85$	Flight idle	Down at 250 KIAS
Landing	Partial unaugmented	20	40	Down	Partial unaugmented	Down

In addition to the procedures shown in table II, thrust was reduced following take-off, as required, to hold the airspeed between 200 and 250 KIAS during heading changes and step-climb operations in terminal area maneuvering. The manually controlled wing-sweep program used for configuration A is presented in figure 10.

As can be seen in figures 8 and 9, for both configurations the climb schedule generally consisted of a segment of constant indicated airspeed, a Mach number and altitude schedule representing a prescribed sonic-boom-overpressure limit, and a final segment of constant indicated airspeed up to the initial cruise conditions. However, for the oceanic

operations with configuration A, the sonic-boom-overpressure limit was eliminated as an operating restriction; and the airplane was flown along the maximum allowable operating-speed (structural) boundary. For some of the domestic departure operations, transonic acceleration was delayed by a subsonic-speed level-flight operation at FL 310 to a designated en route point to place the intensified sonic boom created during transonic acceleration (ref. 8) in an area of low-population density.

The descent schedule for both configurations consisted of a slowup segment at or near cruise altitude with subsequent constant indicated airspeed and constant Mach number segments. For configuration A (fig. 8), a descent to FL 670 was necessary for the slowup phase to ensure sufficient cabin pressurization capability with engines in the flight-idle condition. Also for configuration A, spoilers were deployed at an altitude of 10 000 feet (3.05 km) to expedite the descent. For both configurations, in-flight thrust reversal (available at subsonic speeds) was used in some cases for expediting the descent. In all descents, reduction in speed to an indicated airspeed of 250 knots was made on approach to the terminal area and to lower airspeeds as requested by the ATC approach controller.

Manual inputs were generally used for both horizontal and vertical flight-path control with the Flight Director System providing horizontal and vertical guidance. For vertical guidance along the various climb and descent profiles, the flight-director element of the attitude-director indicator, which was programed to display the pitch-trim input required to return to the Mach number-altitude schedule, was employed.

In order to minimize losses in performance during turns in the supersonic-speed portion of the climbs, a bank-angle-limit schedule was observed by the pilots. The allowable bank-angle-limit schedule was 15° at $M = 1.0$, with bank-angle limit increasing linearly with increase in Mach number to 25° at $M = 2.7$. Bank-angle-limit practice during subsonic flight and in the supersonic portion of the descents was restricted only by conventional airline practice (25° to 30°).

ATC Procedures

In general, for the portions of the departures and arrivals during which the SST was at subsonic speed (below about FL 400), present-day ATC procedures for control of air traffic (ref. 9) were used with no preferential treatment for SST airplanes. For this altitude region, the present-day basic airway structure was used and the division of airspace geographically for ARTCC and airport departure, arrival, and tower-control functions was in accordance with present practice at the facility represented. Airspace below about FL 400 was divided, for control purposes, into two layers; the lower layer extended from the ground to FL 180 and the upper layer extended from FL 190 to about FL 400. The standard instrument departure (SID) and terminal arrival routes were the same or similar

to the routes in present use (fig. 11). All airplanes were subject to step-climb and step-descent operations associated with SID altitude restrictions and handoff (controller-to-controller transfer) procedures. For arrivals, a limit in indicated airspeed of 250 knots was prescribed for the zone within a radius of 30 nautical miles from the airport. Speed changes were requested by the controllers as required for safety and for expediting the flow of traffic. Radar vectoring was used by the controllers to shorten SID and arrival routes when traffic conditions permitted. Standard subsonic jet-transport holding procedures were used for the SST. Holding at 250 KIAS was done at the preferred holding altitudes for minimum fuel consumption, 15 000 to 30 000 feet (4.57 to 9.14 km) for configuration A and 15 000 to 25 000 feet (4.57 to 7.62 km) for configuration B. For altitudes below FL 420, present-day separation standards (for an environment with radar coverage) were used. These standards provided the option of either lateral separation of 3 to 5 nautical miles or specified vertical separation. The specified vertical separation was 1000 feet (0.31 km) below FL 290 and 2000 feet (0.61 km) above FL 290.

For flight at supersonic speeds (above about FL 400), additional ATC handling procedures were specified on the basis of results from previous investigations (refs. 3 and 4). In general, flight at supersonic speeds was specified along parallel one-way track systems (fig. 7). For transition between the basic airway system used at the lower altitudes and the parallel track systems, various arrangements involving existing navigation aids, radar vectors, and fan track systems were used. Above about FL 400, airspace was sectorized geographically into large areas (ultrahigh sectors) (fig. 12). For the Los Angeles environment, the ultrahigh sectors had the same geographical boundaries as the ARTCC boundaries; but for the New York environment, the ultrahigh sectors were independent of existing ARTCC boundaries. In general, the ultrahigh-sector airspace was not divided into altitude layers for control purposes; however, for some domestic operations in the Los Angeles environment, this airspace was divided into two parts – one between FL 390 and FL 450, the other above FL 450. Conflicts between climbing and descending SST airplanes at altitudes above FL 350 were resolved, if possible, by vectoring or leveling the descending airplane to avoid interrupting the transonic acceleration phase of the climbing SST. Holding or circling maneuver instructions were not permitted to be given to airplanes operating at supersonic speeds. For altitudes above FL 420, separation standards of 10 nautical miles horizontally or 4000 feet (1.22 km) vertically were used in an environment with radar coverage. In an environment without radar coverage, the horizontal separation standard was increased to 6 minutes along a track; track separations of 30 and 45 nautical miles were employed in such environments. All airspace above FL 180 in the environments in which tests were made was considered as positive-control airspace.

RESULTS AND DISCUSSION

Ground Tracks

Examples of departure and arrival ground tracks for both oceanic and domestic operations at JFK and at LAX, for oceanic operations at LON, and for domestic operations at SFO are given in figure 13. Mach number values are shown at intervals along the ground tracks and initial cruise (I.C.) points on departures and throttle back (T.B.) points on arrivals are also indicated. The ground tracks shown include examples of standard procedures, radar vectors, and special procedures.

Ground tracks for standard departure and arrival operations to and from the parallel one-way track systems at JFK, LAX, LON, and SFO are given in figures 13(a) to 13(f). Ground tracks for special oceanic departure and arrival operations at JFK to and from a two-way 3-track system (upper routes 1, 2, and 3) are shown in figures 13(g) and 13(h). A comparison of ground tracks for domestic departures from JFK for flights in which transonic acceleration was delayed in order to place the intensified sonic boom created during transonic acceleration (placed superboom) in an area of low-population density with standard departures (unplaced superboom) is given in figure 13(i). An example of a domestic (transcontinental) departure from JFK in which transonic acceleration was performed over the ocean to prevent the superboom from impacting on an inhabited area is shown as run 2, figure 13(b).

Time, Fuel, Distance, and Altitude

Examples of time, fuel, distance, and altitude relationships in departures and arrivals for the same types of operations in the same terminal areas for which ground tracks were shown in figure 13 are given in figure 14. In order to show the effects of terminal area maneuvering, transition to the track systems, and lateral deviations from a great circle route for track-system operations, the results are presented in terms of the distance flown towards destination (great circle distance made good in departures and left to go in arrivals). The results are presented in terms of mission fuel, where mission fuel is defined as item (1) of the the current tentative SST fuel requirements standard. This standard is reproduced in the appendix. The sensitivity of the SST to ATC procedures and handling can be seen by a study of the results given in figure 14. For example, in JFK departures (figs. 14(a) and (c)), the prescribed altitude restriction at 4000 feet (1.22 km) for flying under crossing arrival traffic resulted in use of from 3 to 4 percent of mission fuel during the 5 to 10 minutes spent at this altitude. Use of significant amounts of fuel and time are also evident in the step-descent operations during arrivals in the JFK and LAX areas (runs 1 and 3, fig. 14(b) and runs 1 and 2, fig. 14(f)). Most of the fuel and time used in descents is seen to occur in the altitude range below about

FL 200. The penalties of circuitous routings on fuel and time for JFK domestic departures are indicated by the results for a departure via Huguenot to track upper west 4 (run 1, fig. 14(c)) in which about 7 minutes and 12 percent of mission fuel are used before any distance toward destination is made. Somewhat smaller time and fuel penalties (from 4 to 5 minutes and from 4 to 6 percent of mission fuel) are apparent for JFK oceanic and LAX domestic operations (figs. 14(a) and 14(g)). The effects of lateral deviations required for departure operations on the track systems can be seen by comparisons of the great circle distance made good in JFK departures on the 6-track and 3-track systems (fig. 14(a)) and in the two LAX oceanic departures (fig. 14(e)). The great circle distance made good at initial cruise on the 3-track system at JFK (run 2) is from 15 to 40 nautical miles greater than on the 6-track system (runs 1 and 3) because of the shorter lateral deviations required. Similarly, the great circle distances made good at initial cruise on a LAX departure (run 2) through Perch and Willow (see fig. 13(c)) is about 85 nautical miles greater than on the departure (run 1) through Catalina and Yucca because of the more direct routing.

Comparisons of placed and unplaced superboom operations are given for JFK and LAX domestic departures in figures 14(c) and (g), respectively. For the placed superboom operations shown, approximately 10 minutes were spent in level flight at FL 310 prior to initiation of transonic acceleration. Although from 1.5 to 5 percent more fuel was used at initial cruise conditions in the placed superboom operations as compared with that in the unplaced superboom operations, this apparent penalty in fuel is compensated somewhat by from about 50 to 100 nautical miles greater distance made good in the placed superboom operations. Similarly, the apparent penalties in time at initial cruise conditions for placed superboom operations are compensated somewhat by the greater distances made good. The results for the over-water superboom domestic departure at JFK shows that 20 minutes and 25 percent of mission fuel were expended before any distance toward destination was made good. A comparison of the results for this procedure with the placed superboom operation indicates that at initial cruise conditions, the distance made good was about 200 nautical miles less; however, the amount of fuel used was about 5 percent less, and the elapsed time was about 6 minutes less. A summary of the fuel and time results for unplaced, placed, and over-water superboom operations on the basis of the same distance made good toward destination is discussed in a subsequent section.

Examples of the effects of some nonstandard operations are also illustrated in figure 14. An oceanic arrival at JFK in which descent was initiated about 2 minutes late is shown as run 2, figure 14(b). The late descent initiation required that a long overshoot to the southwest beyond JFK be made to provide time to reduce the altitude sufficiently to land. The overall descent time and fuel usage for this operation were, however, significantly reduced over the standard arrivals (runs 1 and 3) because the time spent in normal step-descent operations was eliminated. Such a result emphasizes the penalty for the SST

in complying with ATC procedures used for handling subsonic airplanes. The effect of an ATC request for slowup to 250 KIAS at FL 280 in a JFK domestic arrival is shown as run 2, figure 14(d). Slowup was effected by use of thrust reversal with a consequent increase of 3 to 4 percent of mission-fuel use over the standard arrivals (runs 1 and 3).

Navigation Problems

General problems.- Navigation problems experienced for the SST in the simulated operations in the ATC systems conceived for the future were similar to those experienced in the tests in the present-day system (ref. 4) - mainly, problems connected with changes in course required at supersonic speeds along the existing airway structure and to effect transition to and from the high-altitude track systems. As discussed in reference 4, turns at supersonic speeds are considered undesirable because of large detrimental effects on performance, the possibility of amplification of the sonic-boom overpressure level, and additional crew workload. Some detrimental effects of turning on SST performance are discussed in a subsequent section. Examples of navigation problems experienced in the present tests are illustrated in the ground tracks given in figure 13. For the JFK area (figs. 13(a) and (b)), undesirable changes in heading were required at just above sonic speed for all departure operations to achieve transition from radar vectors to fan-track systems or airway routes on both oceanic and domestic routes. (Turning at low supersonic speeds is especially undesirable since the capability of the SST to climb and accelerate is a minimum at these speeds.) At higher supersonic speeds, substantial changes in heading (up to nearly 50° in some cases) were required in both departure and arrival operations to achieve transition to and from the track systems for most of the terminal area situations investigated. For such changes in heading, overshoots of the outbound course of up to 10 nautical miles occurred. As discussed in reference 4, such overshoots tend to occur in heading changes at supersonic speeds because of the large turn radii for these conditions which require the pilot to lead the turn by as much, for example, as 30 nautical miles for a 45° heading change at cruise speed. A prime example of large changes in heading required at the higher supersonic speeds was found in the oceanic departures at JFK (fig. 13(a)). For these departures, the transition from the fan-track system to the parallel-track system occurred at about cruise speed. The pilot workload for this situation was noted to be high since in many instances it involved the simultaneous tasks of establishing cruise conditions (altitude and speed) and the outbound heading. Autopilot capability for performing these tasks with flight-director guidance for the manual backup procedure appears to be highly desirable.

In order to alleviate navigation problems in the supersonic acceleration phase of departures, it was advocated in reference 4 that straight-track segments beginning as close to the airport as possible be provided. The benefits of such an approach can be seen in part by a comparison of the ground tracks for the JFK oceanic departures on the

3-track system (fig. 13(g)) and on the 6-track system (fig. 13(a)). In the tests for which the 3-track system was used, both departures and arrivals were made on the three tracks nearest to JFK (upper routes 1, 2, and 3) while in the tests for which the 6-track system was used, the departures were made on the three tracks farthest from JFK (upper routes 4, 5, and 6). It is evident that use of the closer tracks for departures provides the advantages of (a) transition to the fan-track system at subsonic speed, (b) transition to the parallel-track system with smaller changes in heading and at lower speeds, and (c) less overshoot of the outbound course. The preceding discussion, however, should not be construed as an argument for two-way track systems, since as indicated in reference 5, these are considered undesirable from a traffic handling standpoint. Some of the handling problems involved in two-way track systems are shown in figures 13(g) and 13(h).

Because of problems of possible head-on conflict between climbing and descending SST traffic, controllers were forced to deviate airplanes from tracks as can be seen for departure run 1 (fig. 13(g)) and arrival runs 1 and 2 (fig. 13(h)). The deviations from track for arrival runs 1 and 2, since they shortened the arrival distance, also created a problem for the pilot in determining the position at which to initiate descent procedures. For run 1, the deviation from track resulted in a late throttle back and the necessity for considerable lengthening of the path (path stretching) prior to turning to final approach to complete the descent to approach altitude. The necessity of accurate initiation of the slowup for descent is pointed up by the fact that over 6 minutes of flight at 250 KIAS in the terminal area is required for each minute of error in initiating descent unless additional means (spoilers or thrust reversal) can be used to steepen the flight path, in which case part of the time loss can be made up. An example of the path stretching required for a $1\frac{2}{3}$ -minute delay in throttling back for an arrival in the LON area is apparent in run 6 in figure 13(e).

Placement of superboom.- Since limited experiments (ref. 10) indicate that the sonic-boom-overpressure level is amplified by a factor of at least 2 during transonic acceleration as a result of the focusing of the shock waves, the placement of this superboom in areas of low-population density for overland operations has been suggested. In order to study the operational problems involved in the placement of the superboom, the arbitrarily selected areas of low-population density (sterile areas) shown in figure 15 were used for some domestic departure operations from JFK and LAX. Tests were made on two departure routes at JFK and four departure routes at LAX. Three low-population-density areas 20 by 30 nautical miles in area were selected on each of the two JFK departure routes to provide for delay in the start of transonic acceleration because of simulated adverse weather conditions (thunderstorm activity, clear air turbulence, and so forth). The points for initiation of transonic acceleration for placement of the superboom in each of the low-population-density areas are indicated by the arrows. In the placed superboom operations, the SST was flown along the normal climb schedule until optimum

subsonic flight conditions were reached, namely, FL 310 and $M = 0.9$. The SST was then flown in level flight at this speed until the transonic acceleration point was achieved. At this point climb power was reapplied and the climb schedule continued. The transonic acceleration point for each low-population-density area was determined from the sum of the distance required to accelerate from the subsonic FL 310 condition to the altitude and Mach number conditions for onset of the focused shock-wave-propagation phase and the distance from this point to the focal point of the shock waves on the ground. The latter distance was calculated by the method of reference 8. The transonic acceleration points were located about 55 nautical miles ahead of the low-population-density area; the locations of the transonic acceleration points were defined to the pilot as an intersection of a radial bearing from a VOR station with the route. The pilot used the course needle of the course indicator for indication of arrival at the cross-bearing point. The overall accuracy of the simulated VOR navigation system and display was about $\pm 0.5^\circ$, so that for distances from the station to the cross-bearing point for these tests, the transonic acceleration point was indicated to an accuracy of about 0.5 nautical mile. This accuracy is of the same order as that which would be obtained by use of DME in the actual VORTAC system. Examples of the ground tracks and of altitude, fuel, time, and distance relationships for placed superboom operations are given in figures 13(i), 14(c), and 14(g).

For the JFK placed superboom operations, from 6 to 10 minutes of subsonic-speed operations at FL 310 were required before the transonic acceleration point was reached, depending on the route and the low-population-density area selected. The times of subsonic-speed operations at FL 310 at LAX were of the same order and varied from 4 to 9 minutes. The distances involved in these operations varied from about 35 to 88 nautical miles. For the remainder of the placed superboom operation (that is, from the transonic acceleration in climbing flight to the point at which the focused shock-wave-propagation phase was complete), it was found for the SST configurations tested that a straight track approximately 55 nautical miles long would be required to ensure placement of the superboom in the low-population-density area. ATC handling of the SST for the placed superboom operation was indicated to be no problem (ref. 5). However, the operation of the SST in level flight at FL 310 for the times and distances indicated was believed to present potential problems for areas of high-density subsonic jet-transport operations; operation of the SST at higher altitudes for this phase would be preferred. Also, the requirement for the 55-nautical-mile transonic acceleration track with no deviations creates the problem for ATC of providing a block of airspace of this length extending between FL 310 and FL 510.

These time values for the subsonic-speed operations at FL 310 do not reflect corresponding increases in mission time, particularly for those cases where progress is being made toward the destination in this phase. Furthermore, the extra fuel used at subsonic speeds reduces the weight that must be accelerated at the higher speeds, so that

the time for the supersonic acceleration phase is shortened. The penalties in fuel and time for placed superboom operations are discussed in a section to follow.

In order to help define the size requirements for low-population-density superboom placement areas, the along-flight-path error (miss distance) in superboom placement relative to the low-population-density area was calculated for each flight from time histories of the airplane position, speed, and attitude. The miss-distance results for 25 departures are presented in figure 16. The miss-distance results shown include the effects of pilot variation in initiation of transonic acceleration, deviations from the prescribed Mach number and altitude schedule, and deviations from the normal flight-path angle. It can be seen in figure 16 that miss distances up to 11 nautical miles were measured but that most of the miss distances were 2 nautical miles or less. The miss distance of 11 nautical miles was an overshoot, apparently resulting from pilot oversight in initiating transonic acceleration. (A 1-minute delay in acceleration results in a miss distance of this order.) Most of the miss distances, however, were undershoots, believed to result from pilot impatience after up to 10 minutes of level-flight operation to reinitiate the climb. Examination of the data indicated that the combination of the errors from the deviations in climb schedule and flight-path angle contributing to the miss distances shown was less than 0.5 nautical mile and that the largest effect on miss distance is pilot error in time of initiation of transonic acceleration. It should be pointed out that some limited flight experiments (ref. 10) have indicated that the location of the superboom can be predicted by the calculation method used herein to within plus or minus 2 or 3 nautical miles. An additional allowance of this magnitude to the miss distances would thus have to be considered in establishing the size of low-population-density superboom placement areas.

Climbing and descending turns.- In the tests of the SST in the present-day ATC system reported in reference 4, it was found that the SST spent considerable time in climbing and descending turns during the simulated departure and arrival operations. The highest amounts of time spent in climbing and descending turns were found to occur for operations in the JFK area. Most of the time spent in turns occurred at the lower altitudes; that is, in the congested airspace. The changes in heading involved in these turns were necessary because of the requirements of take-off and landing into the prevailing wind, buffer airspace between adjoining airports, community-noise avoidance, ground-navigation-station siting, radar vectoring around other traffic and obstacles, and so forth. These climbing- and descending-turn operations were considered to be undesirable because of the increased crew workload in flying and navigating the airplane and the increased exposure to midair collision by the reduction of forward visibility for the crew and the increase in difficulty of flight-path projection for the air-traffic controller.

For the future ATC system concepts examined in the present tests, the time spent in climbing and descending turns in departure and arrival operations in the JFK area are

given in figure 17. Also shown in figure 17 for comparison are the results for departure and arrival operations in the JFK area in the present-day ATC system environment examined in the tests of reference 4.

From inspection of the results given in figure 17, it is evident that on the average, the time spent in climbing and descending turns for comparable operations and routes is, with one exception, the same for operations in the future ATC system as for the previously measured operations in the present-day ATC system. For the oceanic departures, the average time in turns in the future ATC system was found to be about 2 minutes greater than in the present-day ATC system. This increase in time for the future-system oceanic departures apparently results from the increased heading changes involved in achieving transition from a departure radar-vector track to a fan-track system and, finally, to a parallel-track system (see fig. 11(a)); in the present-day system, oceanic departure transition consisted basically of one heading change from a radar-vector track to an airway route.

Further analysis of the results shown in figure 17(a) indicated that in the departures, from 40 to 95 percent of the time spent in turns occurred in the congested airspace below FL 400, with the highest amounts occurring for the domestic operations. For the arrivals, from 57 to 68 percent of the time spent in turns occurred below FL 200. Comparative results obtained in the departure and arrival operations in the present-day ATC system (ref. 4) showed similar heavy concentrations of the percentage of time in turns in the lower-altitude airspace.

The results just discussed appear to indicate that the amount of terminal area maneuvering required in future ATC systems having the concepts used in the present tests will be of the same order as that required in the present-day ATC system. As discussed in reference 4, it appears that terminal area maneuvering could be considerably reduced by use of climb- and descent-corridor-type operations.

Effects of turns on SST performance.- The detrimental effects of turning at supersonic speeds on SST performance were studied in some special tests of configuration A for 45° changes in course at a cruise Mach number of 2.7. The turns were made at the optimum initial departure cruise altitude, and at 2000 feet (0.61 km) and 4000 feet (1.22 km) above this altitude to represent standard and off-optimum conditions. The turns were performed at bank angles of 10° , 20° , and 30° . The results of these special tests indicated that for altitudes up to 2000 feet (0.61 km) above the optimum, sufficient excess thrust was available to prevent Mach number loss in the turn; however, the 45° course change was made only at the expense of up to an excess fuel use equivalent to 7 percent of the contingency fuel allowance (where the contingency fuel allowance is 7 percent of mission fuel). (See appendix.) For turns made with lower (cruise) thrust during the turn, the fuel used to make the turn and to accelerate back to cruise speed (with full

afterburning thrust) was even higher, varying between 9 and 15 percent of contingency fuel allowance, depending on the altitude and bank angle used. At 4000 feet (1.22 km) above optimum initial cruise altitude, cruise speed could not be maintained during the turn even with full afterburning thrust; and for a bank angle of 30° , the Mach number loss was sufficient to result in enough thrust loss so that it was not possible to accelerate for this condition. Only by descending could cruise speed be regained under these circumstances. For a turn at a bank angle of 20° at this altitude and by using full afterburning thrust, it was possible to accelerate following the turn; however, the excess fuel used in turning and accelerating back to cruise speed was equivalent to 17 percent of the contingency fuel allowance. In summary, appreciable changes in course at cruise conditions were found to create operational problems in maintaining cruise speed, especially under off-optimum conditions, and to result in considerable excess fuel usage. It should be emphasized that similar effects will exist over the entire supersonic-speed range and may be especially penalizing at low supersonic speeds where the minimum excess-thrust condition exists. For these reasons, it is believed that required changes in course, both in angle and in number, for the SST at supersonic speeds must be kept as small as possible.

Operational Problems

Separation of climbing and descending SST traffic.- The ATC separation of climbing and descending SST traffic on possible collision courses above FL 400 where the SST's are at supersonic speeds was found to be complicated by a number of operating limitations for the SST. Because of the slow turning rates which exist at limited bank angles of 25° to 30° (limited to provide low values of acceleration for passenger comfort) and the high closure rates at supersonic speeds, lateral separation is often difficult to achieve. (See ref. 4.) Vertical separation by leveling the climbing airplane was considered to be undesirable because of the high fuel-consumption rates for operation at supersonic speeds and altitudes below cruise conditions. More than several minutes of operations under these conditions could result in a need to abort the mission. The alternative method for vertical separation of leveling the descending airplanes was found to be possible but was found to be constrained by SST operating limitations associated with the relationship of the descent schedule and the boundaries imposed by service ceiling, buffet, and engine blowout (air deficiency).

The relationship of the descent schedule for a sonic-boom overpressure level of 1.5 pounds force per square foot (71.8 N/m^2) and the airplane operating boundaries for SST configuration A are shown in figure 18. For this descent schedule, the airplane is shown to be above its service ceiling from about $M = 2.0$ during the slowdown at FL 670 until it reaches $M = 1.12$ at FL 510. Furthermore, the airplane is near its buffet and engine-blowout boundaries during most of the supersonic-speed part of the descent following the slowup phase. Operation above the service ceiling poses no problems as long

as the descent schedule is followed. However, for level flight above the service ceiling, thrust is insufficient, even in the maximum afterburner thrust condition, to maintain both altitude and speed, with the result that a continuous loss in speed occurs. To complicate the situation, for the engine used, the airplane is also above the afterburner relight boundary for most of the same part of the descent schedule during which it is above the service ceiling, so that the thrust can be increased only to the maximum unaugmented level from the flight-idle condition used in descent. The result of these operating limitations is that for the descent schedule shown, the SST can be leveled in the region of FL 670 to FL 510 only a short time before slowup will occur first to the buffet boundary and second to the engine-blowout boundary. At altitudes between FL 510 and FL 450, the SST is below the service ceiling and can maintain speed and altitude. However, for these conditions, it would be preferable from a fuel-use standpoint to slow to subsonic speed, which would unfortunately place the SST at or near the buffet boundary.

For SST configuration B, although operation above the service ceiling was not required in descent, the descent schedule placed the SST near the service ceiling (to within 20 knots) during the slowdown at cruise altitude. Failure of the pilot to apply maximum afterburning thrust quickly upon leveling would result in a penetration of the service ceiling and development of a situation similar to that described previously for SST configuration A. From a piloting standpoint, in some of the tests with configuration B, altitude restrictions were imposed under conditions where the SST could not be accelerated or climbed. In this situation, the pilots reported that they felt trapped in an untenable position.

It is evident from the previous discussion for the two SST configurations tested that a complex set of ground rules will probably need to be established for ATC in handling altitude restrictions during the supersonic-speed part of the descent of SST airplanes.

As an illustration of the limitations and penalties of altitude restrictions for SST configuration A when operating above the service ceiling, some special tests were made to measure the elapsed times and fuel used between leveling from the descent schedule and penetration of the buffet and engine blowout boundaries shown in figure 18. The measurements were made at FL 550, FL 600, FL 630, and FL 670. For one set of tests, the thrust setting was left in the descent-flight idle condition throughout leveling and the slowup; for another set of tests, the thrust setting was advanced on leveling to the maximum unaugmented condition. Results from these tests are given in figure 19.

The elapsed-time results shown in figure 19 indicate that unless thrust is increased from the flight-idling condition when the airplane is leveled at the altitudes shown, the buffet boundary is reached within from 1/2 to 2 minutes and the engine blowout boundary is reached about 1/2 minute later. When thrust is increased to the maximum unaugmented condition on leveling, the elapsed times to the buffet boundary are increased by $1\frac{1}{2}$

to 4 minutes and to the engine blowout boundary by $2\frac{1}{2}$ to $5\frac{1}{2}$ minutes. It should be pointed out that if turns were required during slowdown, these times would be decreased. These results make it apparent that ATC can assume that only very short leveling times are available for SST airplanes such as configuration A at the altitudes where the descent schedule lies above the service ceiling. Further, pilot error in failing to increase thrust on leveling would lead to a considerable reduction in the expected available leveling time. The penalties in extra fuel consumption for altitude restrictions in this flight region are also shown in figure 19. In the flight-idling thrust condition, the fuel used between leveling and the buffet and engine blowout boundaries was found to be negligible. In the maximum unaugmented thrust condition, however, the fuel used was found to be appreciable, varying from 5 to 15 percent of the contingency fuel allowance in slowup to the buffet boundary and from 8 to 20 percent in slowup to the engine blowout boundary. In this thrust condition for this flight region, leveling time for ATC collision avoidance procedures is bought at the expense of from 3 to 4 percent of contingency fuel allowance for each minute of operation.

In summary, it appears that separation of climbing and descending SST traffic on a collision course at supersonic speeds can probably best be effected by imposing altitude restrictions on the descending airplane. However, the time available for leveling a descending SST at supersonic speeds may be severely constrained because of high fuel-consumption rates and because of required operations above the service ceiling and near the flight limit boundaries.

Communications workload.- In order to illustrate the crew workload involved with ATC communications in the simulated operations of the SST in the future ATC system, the percent of time spent on ATC communications in departure and arrival operations was analyzed. The time spent on ATC communications was taken as the time spent in transmitting and receiving messages and does not include time spent waiting for a clear channel. Only the messages during flight operations were included; that is, for the departures, the messages between and including clearance for take-off and reporting of cruise conditions, and for the arrivals, the messages between and including the entry-position report and the touchdown-on-the-runway report. The messages involved position reports; altitude reports; communication-frequency change and speed requests; take-off, altitude, route, and ILS clearances; radar vectors; weather and runway-in-use information; and identification confirmation. Results of this analysis for JFK oceanic and domestic departure and arrival operations in the future ATC system are given in figure 20. Also shown in figure 20 for comparative purposes are the results from the analysis of JFK domestic departure and arrival operations in the present-day ATC system reported in reference 4.

For both the entire arrival and departure intervals, the time spent on ATC communications for both oceanic and domestic future-system operations is seen to be on the average about the same as found for the previous tests in the present-day ATC system.

The overall air-to-ground communication workload in the future system does not appear from these results to be any less than in the present-day system, even with the provision of alpha-numeric information on the controller's displays. Analysis of message content indicated that most messages were concerned with such items as descent clearances, radar vectors, and handoff instructions rather than with the identification, altitude, and speed information provided by the alpha-numeric display. For the several individual 10-minute periods analyzed, the time spent in ATC communications in both oceanic and domestic arrival and departure operations in the future system varied only a few percent from the time spent in the present-day system. In arrivals, however, the largest average value occurred in the 10 to 20 minutes prior to touchdown for the future system in contrast to the increase in average values in succeeding time intervals as touchdown was approached for the present-day system. The trend of average values with time intervals for departures was the same in the future system as in the present-day system - highest for the first 10-minute interval after take-off and decreasing in succeeding time intervals.

The time spent on ATC communications was also analyzed for the special operations at JFK involving (1) placement of the superbloom in a low-population-density area in departures and (2) departure and arrival operations on the two-way 3-track oceanic system. Results are shown in figure 21. Shown for comparison are results for departures on the same routes in which the superbloom was unplaced and results for departures and arrivals on the one-way 6-track system. On the average, the time spent on ATC communications is seen to be increased about 2 percent for the placed superbloom departures over the results for unplaced superbloom departures, so that the additional crew-controller coordination for supersonic flight clearance on the placed superbloom departures appears to be small. Comparison of the results on the 3- and 6-track systems indicates that, on the average, no appreciable increase in ATC communication time was necessary in either departures or arrivals in handling the SST on the two-way 3-track system over the time required on the one-way 6-track system.

Fuel and Time Penalties of Operations in ATC System

Maneuver time and fuel.- The range and average values of maneuver time and fuel used in the departure and arrival operations at JFK, LAX, SFO, and LON are shown in figure 22. Maneuver time and fuel are defined as the additional time and fuel used above the time and fuel required for an unrestricted straight climb or descent and, hence, are measurements of the penalties of such maneuvers as altitude restrictions connected with flying over or under crossing traffic and with controller handoff procedures, of being radar vectored to avoid restricted airspace and other traffic, of indirect routings required in the use of the airways system, and of the lateral deviations required in transition to or from the track systems. The maneuver-fuel results are presented in terms of mission fuel, where mission fuel is defined as item (1) of the tentative SST fuel requirements

standard listed in the appendix. Also shown in figure 22 is the en route contingency fuel allowance (7 percent of mission fuel) provided by item (2) of the same standard. Since this standard does not provide any separate allowance for maneuvering fuel, the en route contingency fuel provided by this standard has been assumed to be the source of fuel required for maneuvering.

For the standard domestic departures (unplaced superboom operations) at JFK (fig. 22(a)), the average maneuver time was found to be 5.8 minutes and the average maneuver fuel was found to be 4.1 percent of mission fuel. The corresponding average values for oceanic departures on the 6-track system were found to be 8.8 minutes and 5.6 percent, respectively. On the average, therefore, in the domestic departures from JFK, about 59 percent and in the oceanic (6-track system), about 80 percent of the contingency fuel allowance was consumed in terminal area maneuvering. For two oceanic departures, over 100 percent of contingency fuel was used for maneuvering. The relatively larger average time and fuel values for oceanic departures compared with those for domestic departures apparently resulted from the larger deviations required to effect transition to the track system and the additional turning required at supersonic speeds. (See figs. 13(a) and 13(b).) The least amount of maneuvering fuel, on the average, was used on the oceanic departures on the 3-track system, although, the least maneuvering time was used in the domestic departures. The lower value of maneuvering fuel used on the oceanic departures on the 3-track system as compared with that on the domestic departures apparently resulted from the smaller amount of supersonic-speed turning required, especially at transonic speeds. (See figs. 13(g) and 13(b).) Placed superboom and over-water superboom domestic-departure results shown in figure 22(a) are discussed in a subsequent section.

For the standard domestic departures (unplaced superboom operations) at LAX (fig. 22(b)), the average maneuver time was 2.6 minutes and the average maneuver fuel used was 1.3 percent of mission fuel. The corresponding average values for oceanic departures were 2.4 minutes and 0.4 percent. Terminal area maneuvering required in departures from LAX thus consumed about 19 percent in domestic operations and about 6 percent in oceanic operations of the contingency fuel allowance. The considerably smaller values of maneuver time and fuel for standard domestic- and oceanic-departure operations at LAX as compared with the same operations at JFK are the result of smaller lateral deviations to effect transition to the track system and less turning required at supersonic speeds. (See figs. 13(c), 13(d), 13(a), and 13(b).) Comparison of the LAX and JFK maneuver time and fuel results emphasizes (as discussed in ref. 4) the importance of providing for the SST operations as near as feasible to the unrestricted climb-corridor type.

For the domestic arrivals at JFK (fig. 22(c)), the average maneuver time was 1.6 minutes and the average maneuver fuel used was 1.5 percent of mission fuel. The

corresponding average maneuver time and fuel values for the oceanic arrivals from the 6-track system were 12.3 minutes and 4.8 percent. On the average, therefore, in the JFK domestic arrivals about 21 percent and in the oceanic arrivals (6-track system) about 69 percent of the contingency fuel allowance was used in terminal area maneuvering. The relatively smaller average time and fuel values for domestic arrivals compared with those for oceanic arrivals apparently resulted from the smaller deviations required to effect transition from the track system. (See figs. 13(b) and 13(a).) The smaller average time and fuel values for oceanic arrivals on the 3-track system compared with those on the 6-track system resulted from more direct routing associated with radar vectoring for traffic separation. (See figs. 13(h) and 13(a).)

For the domestic arrivals at LAX (fig. 22(d)), the average maneuver time was 7.7 minutes and the average maneuver fuel used was 1.4 percent of mission fuel. The corresponding average maneuver time and fuel values for the oceanic arrivals were 7.8 minutes and 1.8 percent. Terminal area maneuvering required in arrivals at LAX thus consumed about 20 percent in domestic operations and about 26 percent in oceanic operations of the contingency fuel allowance. The amount of maneuvering fuel used in the domestic and oceanic arrivals at LAX was of the same order as that used in the domestic arrivals at JFK (fig. 22(c)). The arrival maneuver times at LAX were generally considerably greater than the maneuver times for domestic arrivals at JFK because of the early reduction in indicated airspeed to 250 knots requested by the controllers at distances from 39 to as much as 112 nautical miles from the airport. The restriction in airspeed to 250 knots was imposed for the purpose of sequencing traffic (flow control).

The maneuver time and fuel results from a limited number (four to six each) of departure and arrival operations at SFO and LON are shown in figure 22(e). For the arrivals, maneuver time and fuel values are seen to be greater on the average than for the departures. Examination of the track-system arrangements for these areas (figs. 13(f) and 13(e)) indicates that, in both cases, the lateral deviations required in the transition from the track system in arrivals are greater than the deviations required in transition to the track system in departures.

In summary, maneuver fuel measurements made in JFK departure and arrival operations indicate that for any one operation, large amounts (average values up to 80 percent) of the contingency fuel allowance can be used in complying with ATC flight-path restrictions and indirect routings connected with operations along the airways system and to and from high-altitude parallel-track systems. For the LAX departure and arrival operations where the restrictions were fewer and the routings more direct, the use of maneuver fuel was small (average values up to 26 percent of the contingency fuel allowance). These results indicate that provision for departure and arrival maneuvering

fuel should be included in the airworthiness standards for supersonic transports to prevent large drains on, or even complete consumption of, the en route contingency fuel in the terminal area maneuvering operations.

Superboom placement.- The penalties in maneuver time and fuel for placement of the superboom in JFK and LAX domestic departures can be seen by comparison of the results for placed and unplaced superboom operations in figures 22(a) and 22(b). For the JFK domestic operations, the penalties in time and fuel for departures made to place the superboom over the ocean can be seen by comparison of the results for over-water operations with those for unplaced superboom operations. For the JFK departures, the placed superboom operations increased the maneuver time on the average by 5.6 minutes and the maneuver fuel by 3.1 percent of mission fuel. Use of the over-water routing increased the average maneuver time and fuel by the same order as the placed superboom operations and indicate that such routing might be feasible for domestic JFK operations if the superboom is required to be placed in an uninhabited area. The penalties in maneuver time for the LAX placed superboom operations were essentially the same on the average as those for the same operations at JFK; however, the average maneuver fuel penalty was lower (only 0.3 percent of mission fuel). This relatively low penalty in maneuver fuel for the LAX placed superboom operations resulted from the better subsonic flight efficiency of the variable-wing-sweep SST configuration used in these operations as compared with that of the fixed-wing SST configuration used in the JFK operations.

Mission analysis.- An analysis of the effects of operations in future ATC systems on transatlantic and transcontinental missions made by use of the maneuvering fuel and time results of figure 22 is presented in figure 23. Results for missions from JFK to LON, LON to JFK, JFK to SFO, and SFO to JFK are given. All of these missions are for results measured with the fixed-wing SST configuration B.

For this analysis, the high, low, and average values of maneuver fuel measured in the departure and in the arrival operations were combined with calculated cruise fuel to obtain extreme and average total fuel requirements for each of the four missions. For each mission, the take-off gross weight and city-to-city distance were held constant. The cruise fuel was calculated on the assumption that the cruise part would be operated in constant Mach number cruise-climb flight at the altitudes to optimize the flight efficiency factor (ratio of the product of Mach number and lift-drag ratio to the specific fuel consumption). Thus, the initial cruise altitude was assumed to be adjusted for the differences in initial cruise weight, and the cruise fuel was calculated on the basis that the ratio of final cruise weight to initial cruise weight was a constant value. The total fuel-requirement results given in figure 23 for each mission are expressed in percentage of the fuel requirements for the basic missions (unrestricted climb and descent operations) and, thus, show the penalties for operations in the future ATC systems. The fuel values for the basic missions are equivalent to the mission fuel values specified as item (1) in

the standards given in the appendix. Also shown in figure 23 for comparative purposes is the total of specified mission fuel and en route contingency fuel (107 percent of mission fuel). The extreme and average values of increase in block time shown in figure 23 were obtained by totaling the high, low, and average values of maneuver time measured in the departure and arrival operations (fig. 22). The increase in block-time values thus represent the penalties in time for mission operations in the future ATC systems.

The results shown in figure 23 indicate that for the transatlantic missions and the JFK to SFO transcontinental mission the total fuel requirements would exceed about 104 percent of mission fuel for all flights and in extreme cases could exceed the total of mission and en route contingency fuel by substantial amounts. The smaller total fuel requirements for the SFO to JFK transcontinental mission compared with those for the other missions are attributed to the more direct routings for this mission. On the average, the total fuel required was found to exceed the mission fuel requirements by from about 6 to 7.5 percent of mission fuel for the transatlantic missions and by from about 2 to 6.5 percent of mission fuel for the transcontinental missions. For the missions originating at JFK, the total fuel required on the average was of the order of the total of the mission and contingency fuel. For transatlantic missions, the results in figure 23 indicate that the block time would be increased on the minimum by about 11 minutes for operations in the ATC system and in extreme cases could be increased by more than 24 minutes. The results also indicate that the block time for transcontinental missions in the ATC system would be increased from about 6 minutes on the minimum to over 20 minutes in extreme cases for JFK to SFO operations and from about 2 minutes on the minimum to about 9 minutes in extreme cases for SFO to JFK operations. The smaller block-time increases for the SFO to JFK mission compared with those for the other missions is attributed to the more direct routings. On the average, block times were increased from 17 to 18 minutes for the transatlantic missions and from 5 to 11 minutes for the transcontinental missions. These total fuel-requirement and increase in block-time results confirm the conclusions reached in previous sections regarding the need for provision of departure and maneuver fuel allowances in the airworthiness standards for supersonic transports and the need for direct routings.

CONCLUDING REMARKS

The results of an investigation of the problems for the supersonic transport (SST) connected with operations in future Air Traffic Control (ATC) system environments conceived for the time period for introduction of the SST into service have been presented. The studies were conducted by means of real-time simulation by use of an SST aircraft flight simulator and the Federal Aviation Administration's ATC simulation facilities. The aircraft flight simulator was operated by airline crews and the ATC simulation

facilities were manned by experienced air-traffic controllers. Two SST design-study configurations, one having a variable-sweep wing and the other a fixed double-delta wing, were used in the studies. The test program included departure and arrival operations under Instrument Flight Rule conditions in the New York, Los Angeles, San Francisco, and London terminal areas. The principal results are:

1. For the future ATC system concepts investigated, substantial changes in course (up to nearly 50°) at supersonic speeds were required in many instances on the airway routes and to effect transition to and from the high-altitude track systems. Such changes in course at supersonic speeds were detrimental to SST performance and increased the workload for the crew.

2. The effects on SST performance of turning at supersonic speeds measured under off-optimum conditions at cruise speed indicated that a 45° change in course could be made only at bank angles of 20° or less without affecting performance to the degree that only by descending could the speed lost in the turn be regained. At a bank angle of 20° , the excess fuel required to turn and regain speed under these conditions was equivalent to 17 percent of the contingency fuel allowance.

3. The time spent in climbing or descending turns in departure and arrival operations in the future ATC system in the New York area was, on the average, of the same order or greater than that found in previous tests in the present-day ATC system.

4. For the future ATC system concepts investigated, substantial amounts of maneuver fuel were required for complying with ATC flight-path restrictions and for following indirect routings along the airways and to and from the high-altitude track systems. On a mission basis, the calculated total fuel requirements on the average were found to exceed the mission fuel requirements provided under the Tentative Airworthiness Standards for Supersonic Transports (Nov. 1, 1965; Revision 4, Dec. 29, 1967) by from about 6 to 7.5 percent of mission fuel for the transatlantic mission and from about 2 to 6.5 percent of mission fuel for the transcontinental mission. Corresponding maneuver times were found to increase mission block times on the average from about 17 to 18 minutes for the transatlantic missions and from 5 to 11 minutes for the transcontinental missions.

5. Extended subsonic-speed operations in domestic departures from New York and Los Angeles made to place the amplified sonic boom created in transonic acceleration on areas of low-population density increased the maneuver time on the average by 5.6 minutes. In these operations, the maneuver fuel was increased on the average by 2.8 percent of mission fuel for the SST design with the double-delta wing in the New York departures and by 0.3 percent of mission fuel for the SST design with the variable-sweep wing in the Los Angeles departures. Miss distances in placement of the amplified sonic boom were calculated to be 2 nautical miles or less for most of the operations.

6. The time spent on ATC communications in departure and arrival operations in the future ATC systems in the New York area was on the average about the same as that found in previous tests in the present-day ATC system.

7. The time available for leveling a descending SST airplane for traffic-separation purposes at supersonic speeds may be severely constrained because of high fuel-consumption rates and because of required operations above the service ceiling and near the flight limit boundaries.

Langley Research Center,
National Aeronautics and Space Administration,
Langley Station, Hampton, Va., August 6, 1968,
720-04-00-17-23.

APPENDIX

FAA TENTATIVE STANDARD FOR SST FUEL REQUIREMENTS

The FAA Tentative Standard for SST Fuel Requirements (FAR 121.648) is taken from reference 11. The SST will be required to carry:

- (1) Sufficient fuel to proceed from departure to destination (includes taxi, take-off and climb, transonic acceleration, cruise, descent and one instrument approach at destination to touchdown); plus
- (2) En route contingency fuel, 7 percent of (1); plus
- (3) Fuel to execute a missed approach at destination, climb out, and cruise to alternate, arriving there at 1500 feet (0.46 km); plus
- (4) Fuel to hold at alternate for 30 minutes at 1500 feet (0.46 km) at standard temperature; plus
- (5) Fuel for one instrument approach and land at alternate.
- (6) Further, the total fuel on board shall be sufficient to permit, in the event of the failure of two engines at the most critical point en route, continuation to a suitable airport forecast to be available for landing, and arrive thereat with sufficient fuel remaining to fly for 15 minutes at 1500 feet (0.46 km) under standard temperature conditions.

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5. Sluka, Andrew L.: ATC Concepts for Supersonic Vehicles – Part II-1. Rep. No. RD-67-38, FAA, Aug. 1967.
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7. Silsby, Norman S.; and Fischer, Michael C.: A Simulator Study of a Pictorial Navigation Display in Instrument Departures of the Supersonic Transport. NASA TN D-4029, 1967.
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9. Anon.: ATC Procedures. AT P 7110.1B, FAA, Nov. 12, 1964.
10. Lansing, Donald L.; and Maglieri, Domenic J.: Comparison of Measured and Calculated Sonic-Boom Ground Patterns Due to Several Different Aircraft Maneuvers. NASA TN D-2730, 1965.
11. Anon.: Tentative Airworthiness Standards for Supersonic Transports. Flight Standards Service, FAA, Nov. 1, 1965; Revision 4, Dec. 29, 1967.

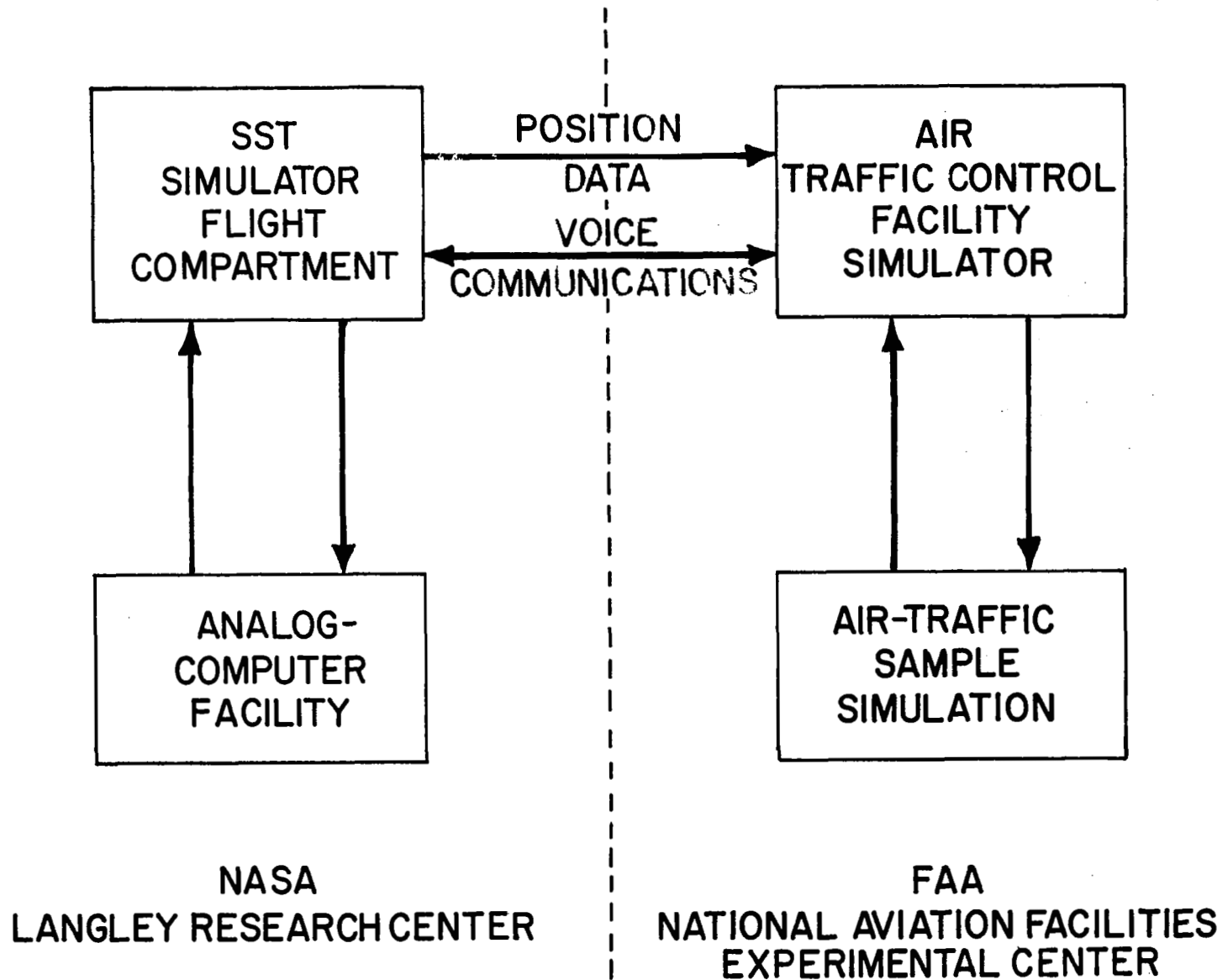


Figure 1.- Diagram of SST ATC simulation method.

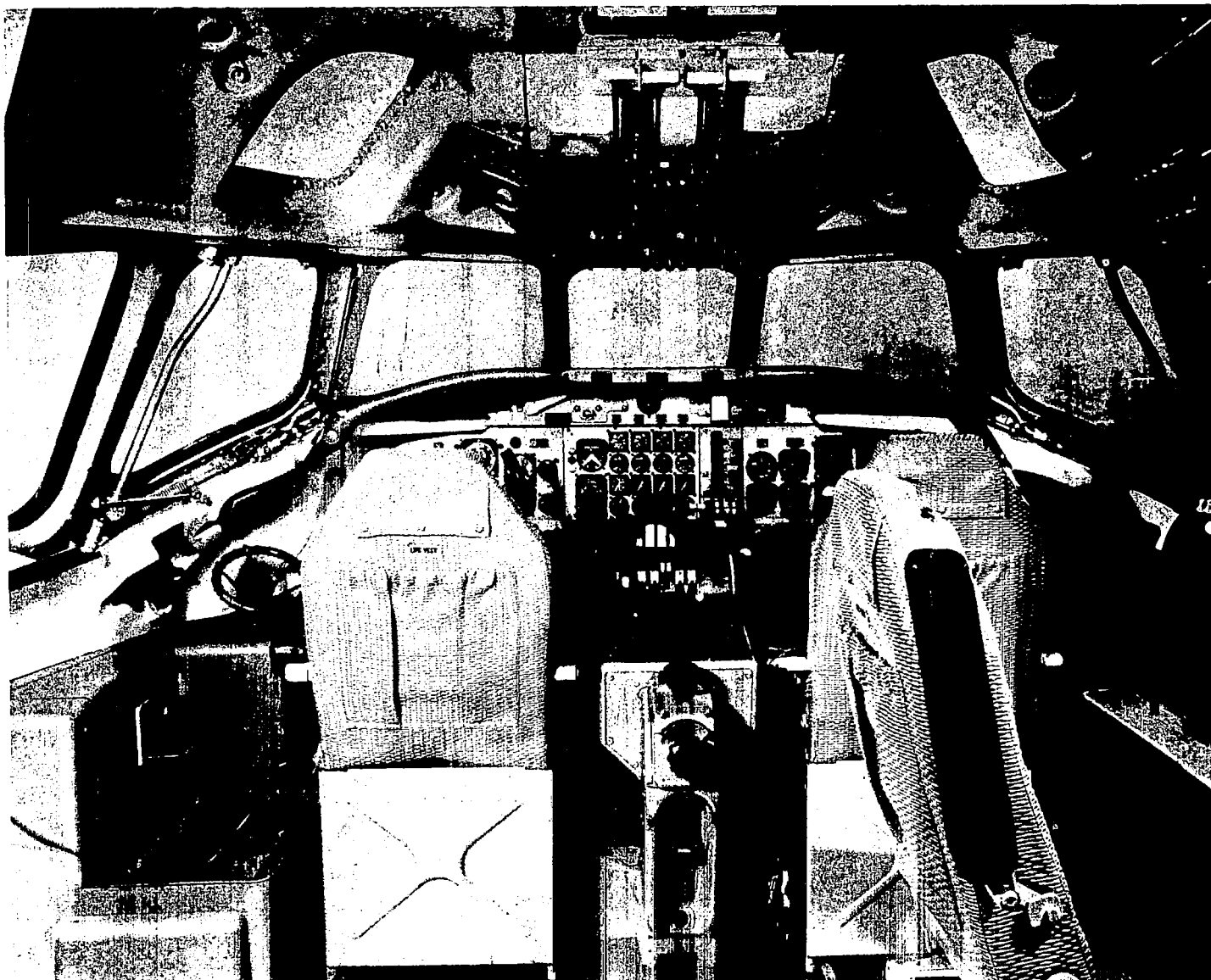


Figure 2.- Fixed-base SST simulator cockpit at LRC.

L-68-8589

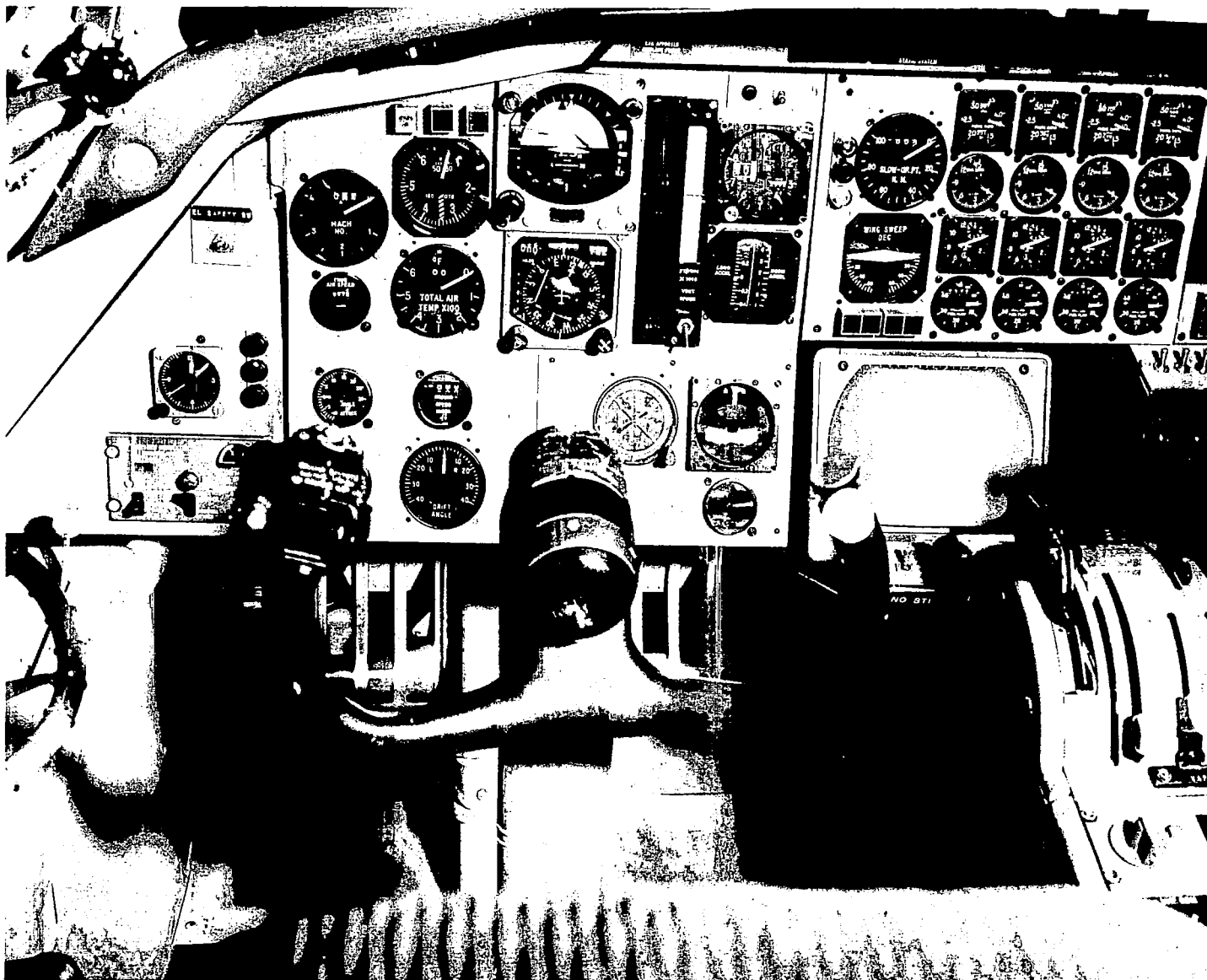


Figure 3.- Captain's flight instrumentation.

L-67-2805

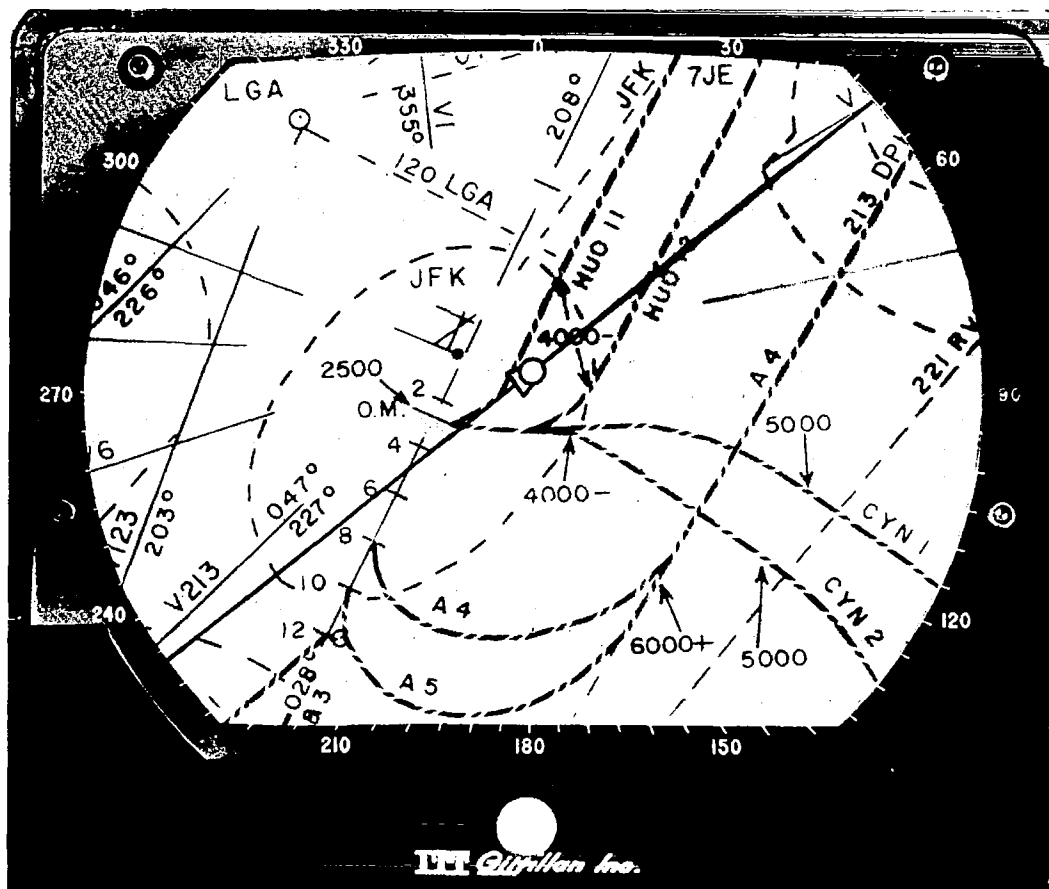


Figure 4.- Pictorial navigation display. (Approximately 2/3 full scale.)

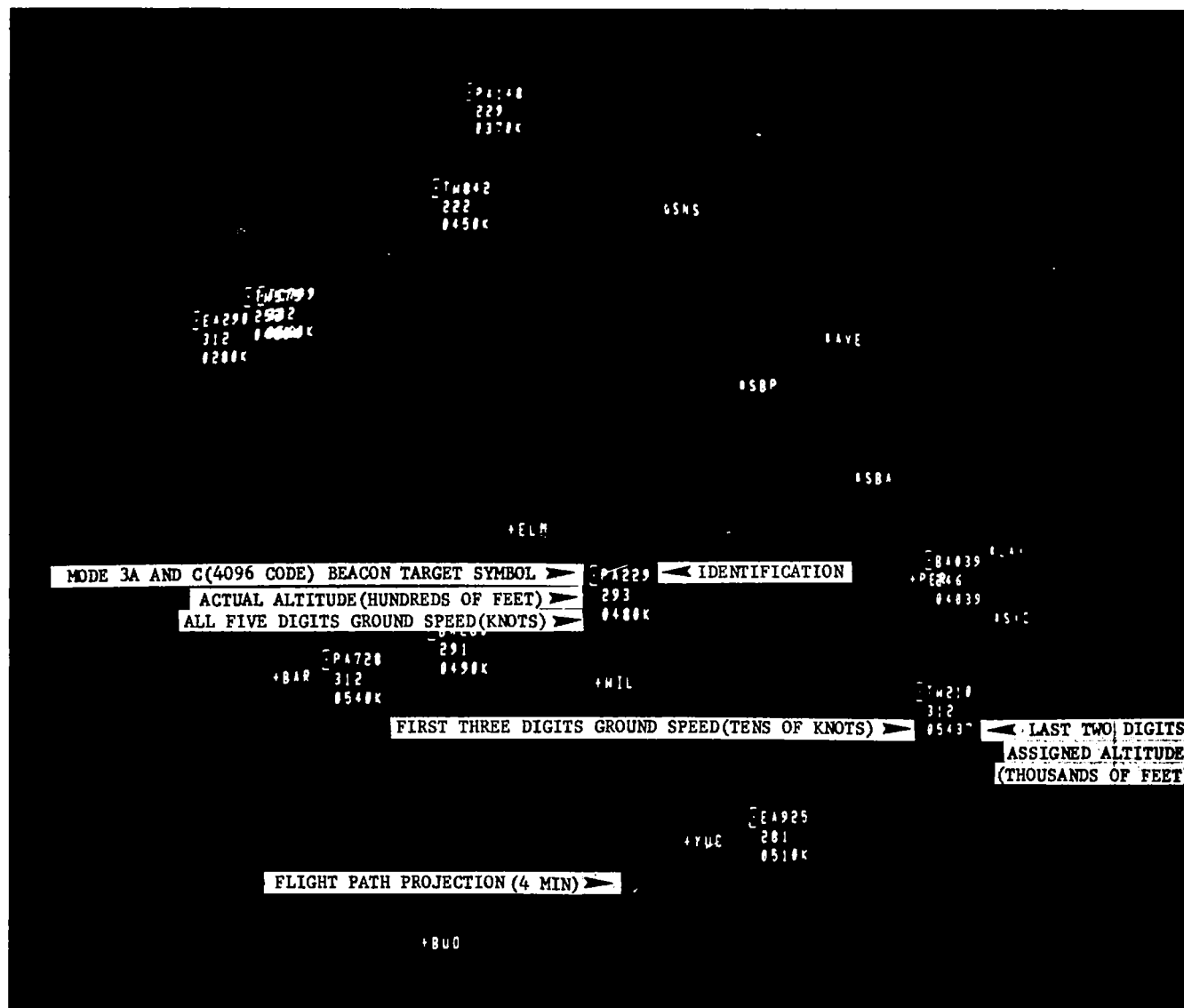


Figure 5.- Display of airplane target symbols and target identification and altitude tags on cathode ray tube. Symbol identification information is superimposed for explanatory purposes. Two alternative methods of displaying information on the third line are shown.

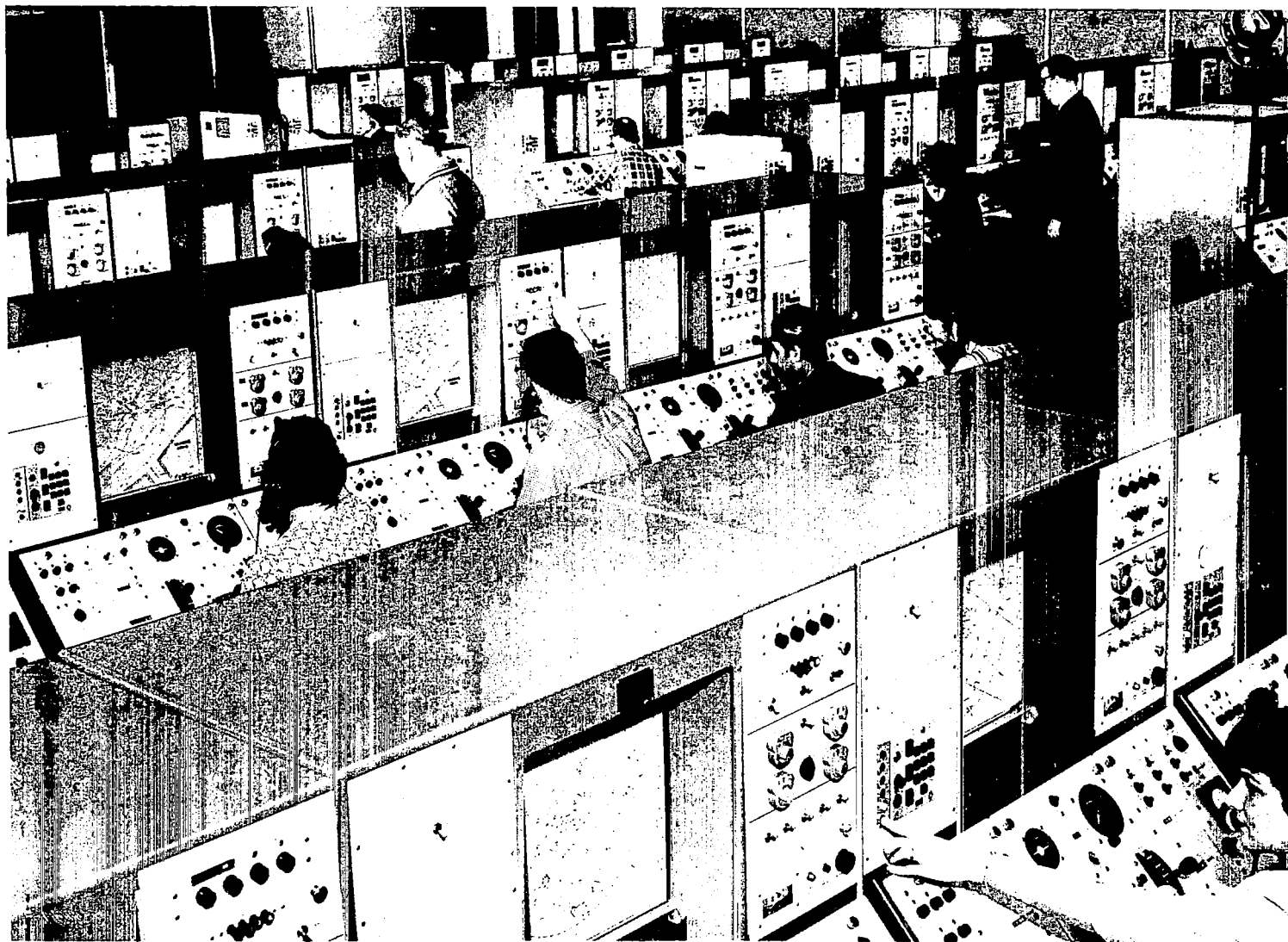
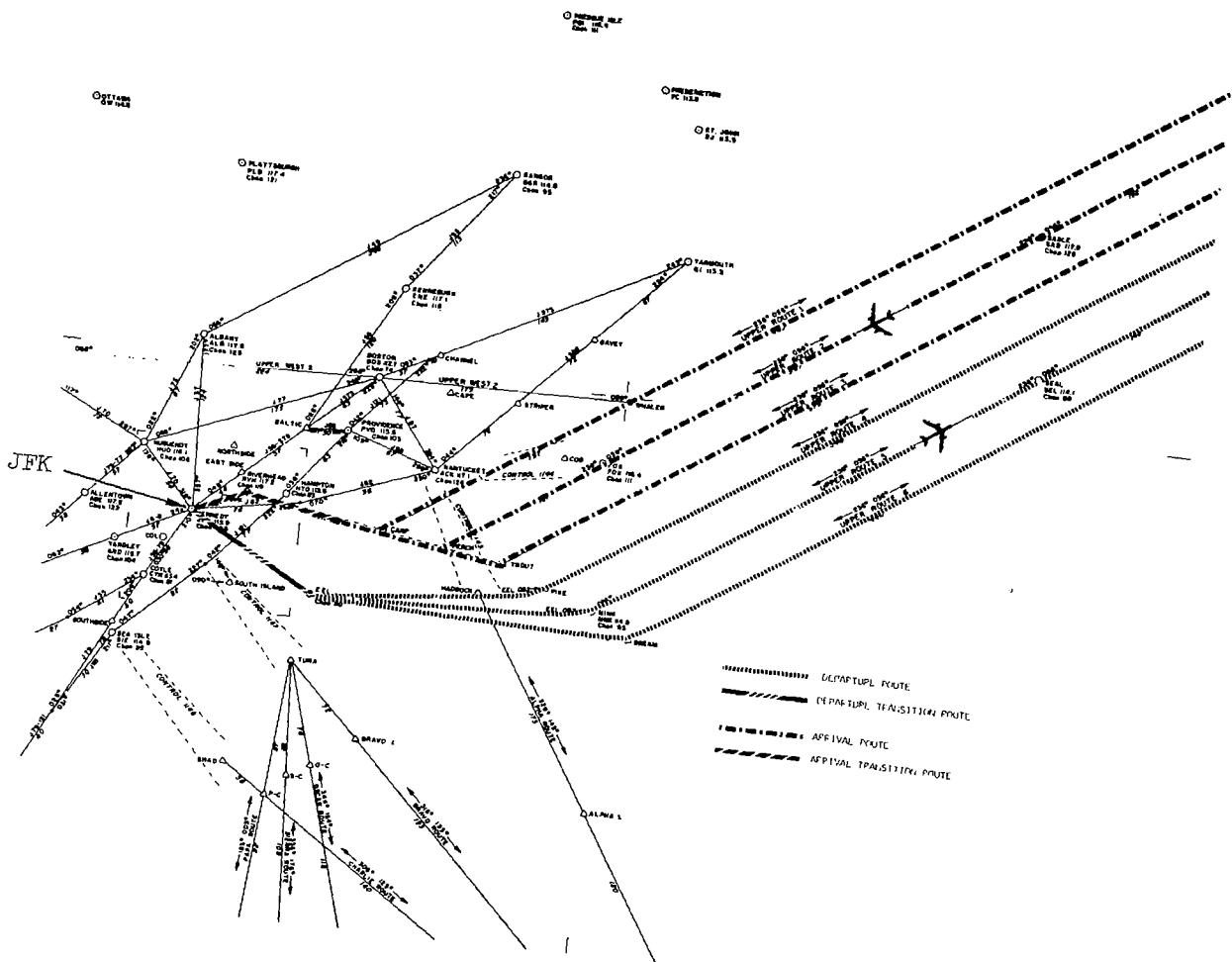


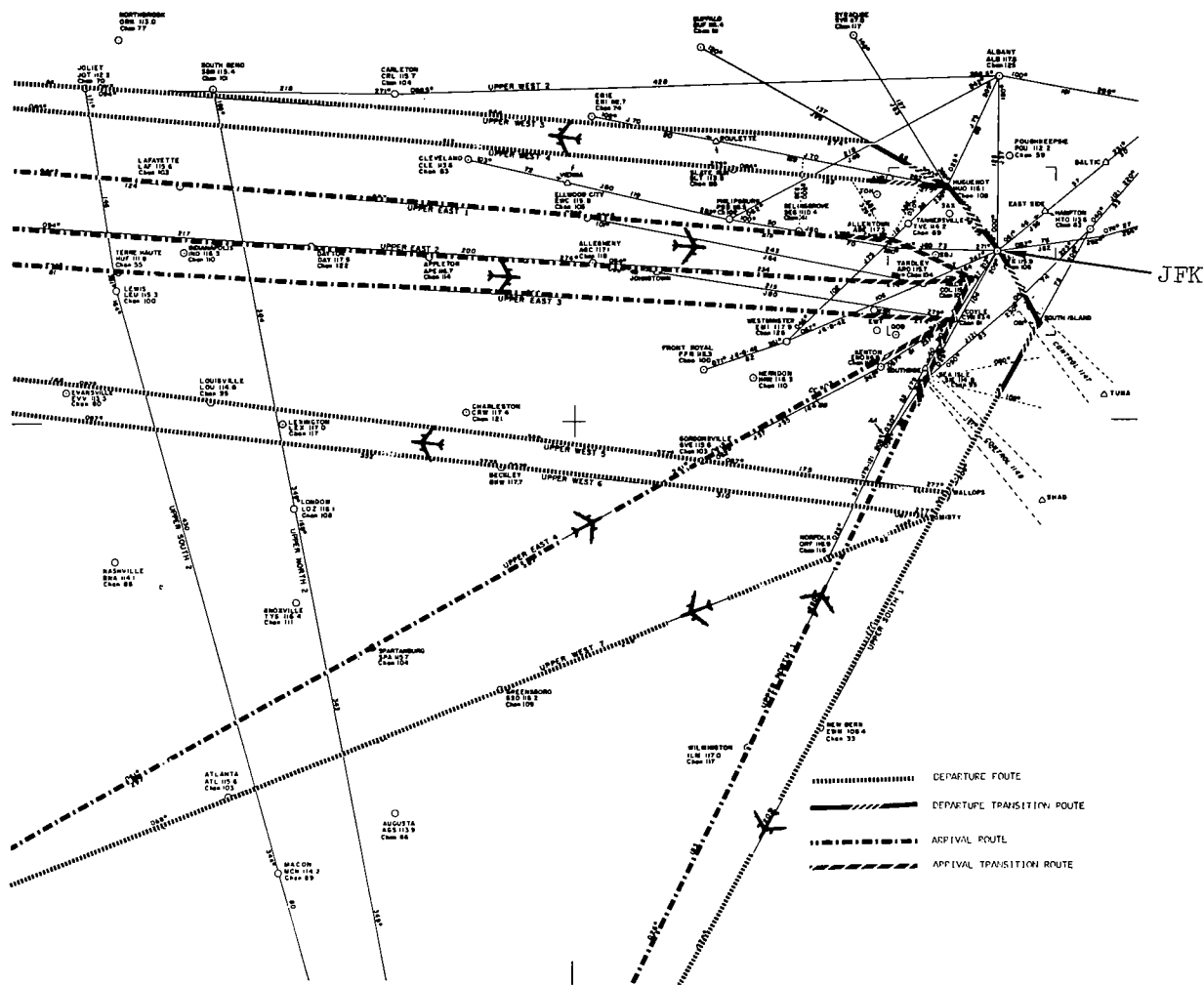
Figure 6.- Radar-target generators.

L-68-8590



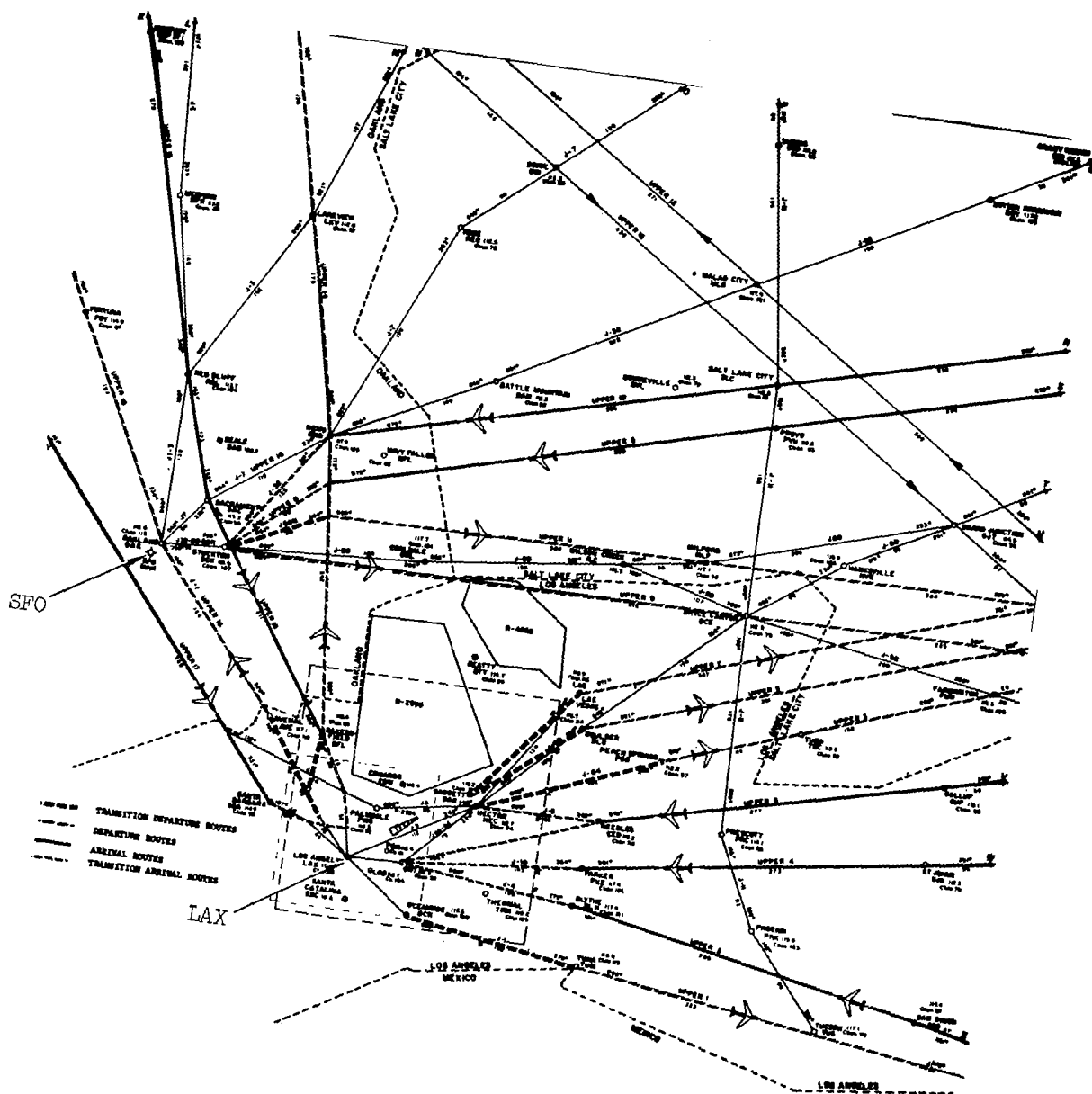
(a) JFK oceanic.

Figure 7.- Test environments and route structures.

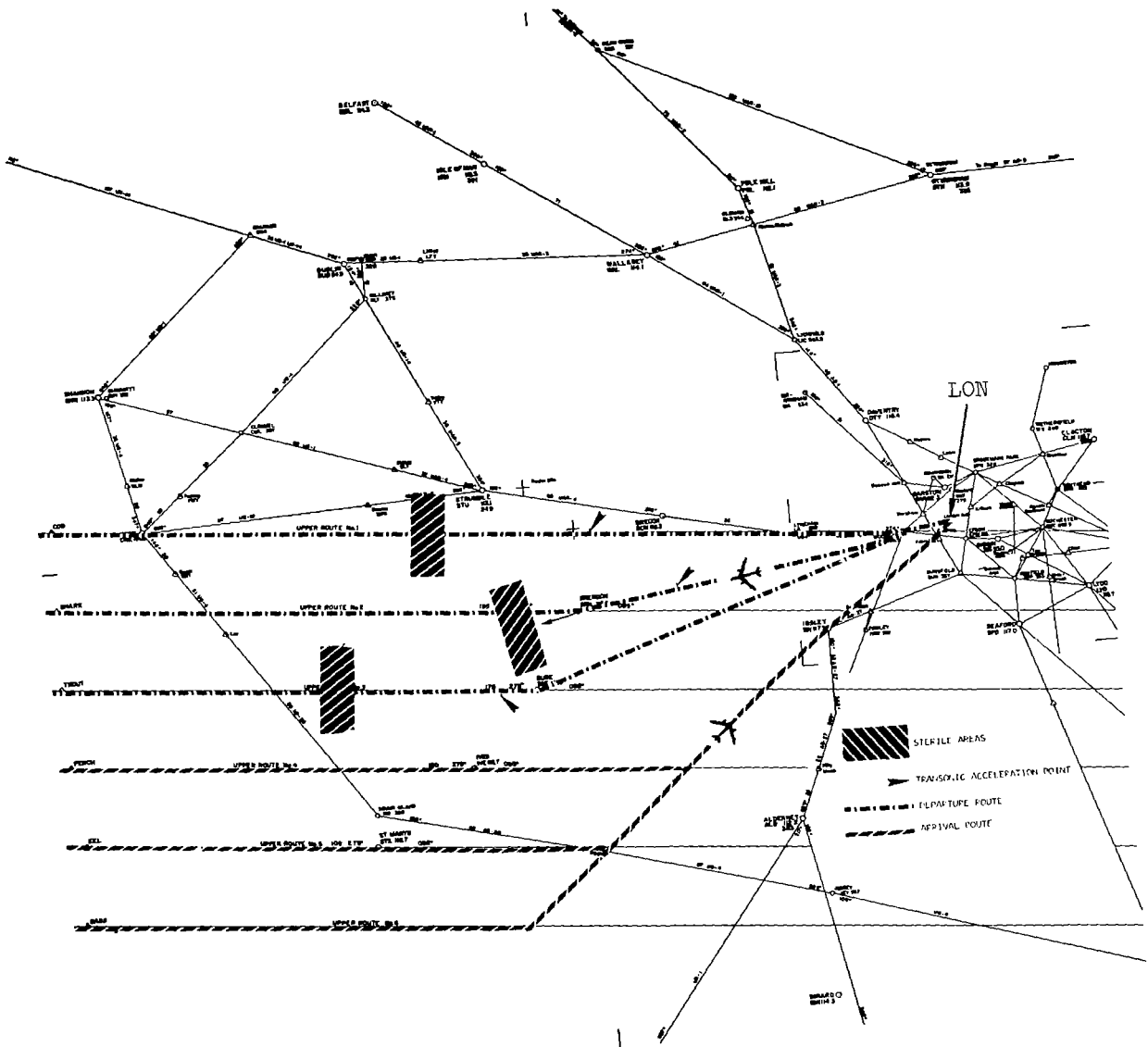


(b) JFK domestic.

Figure 7.- Continued.

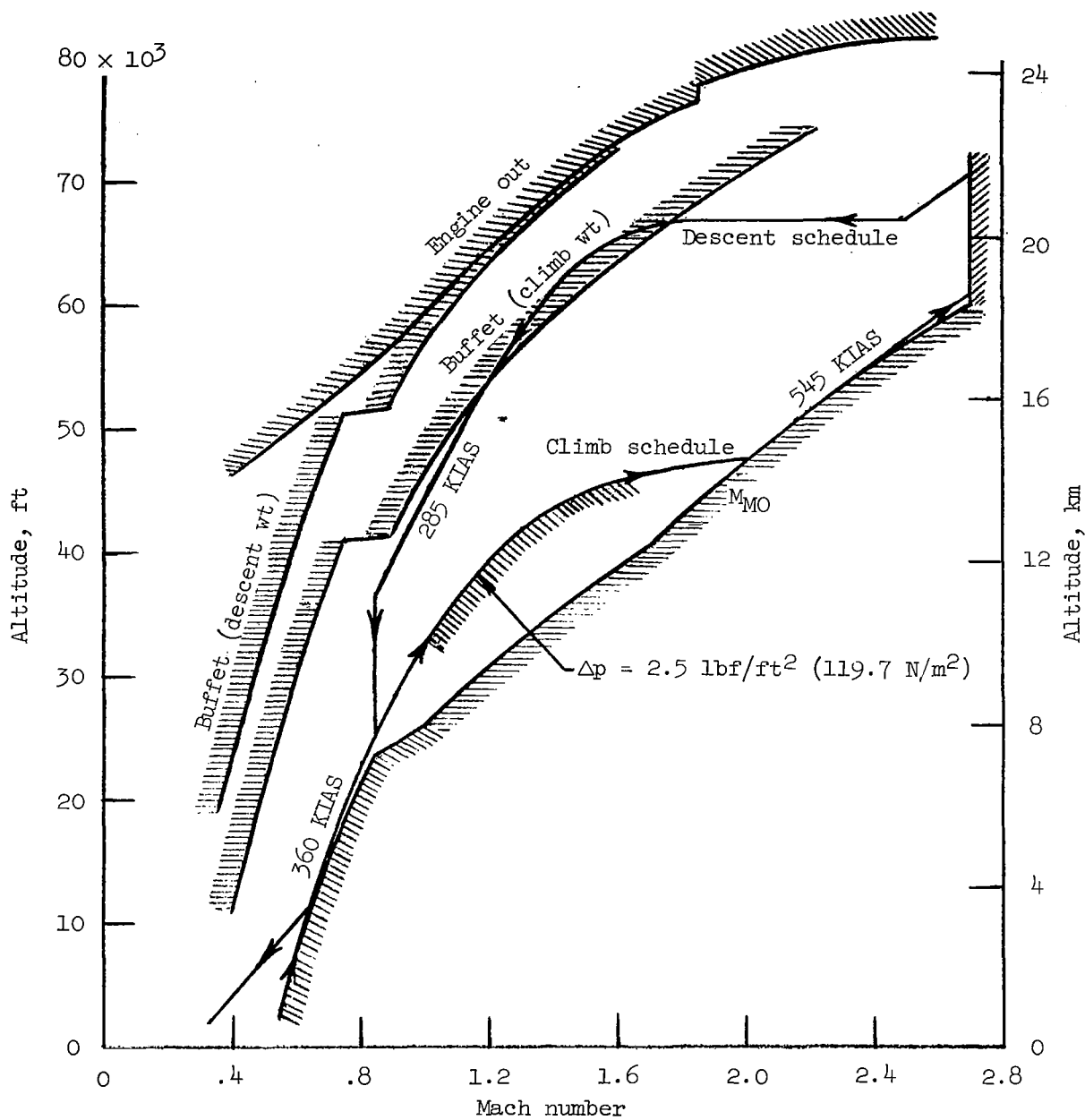


(d) LAX domestic.
Figure 7.- Continued.



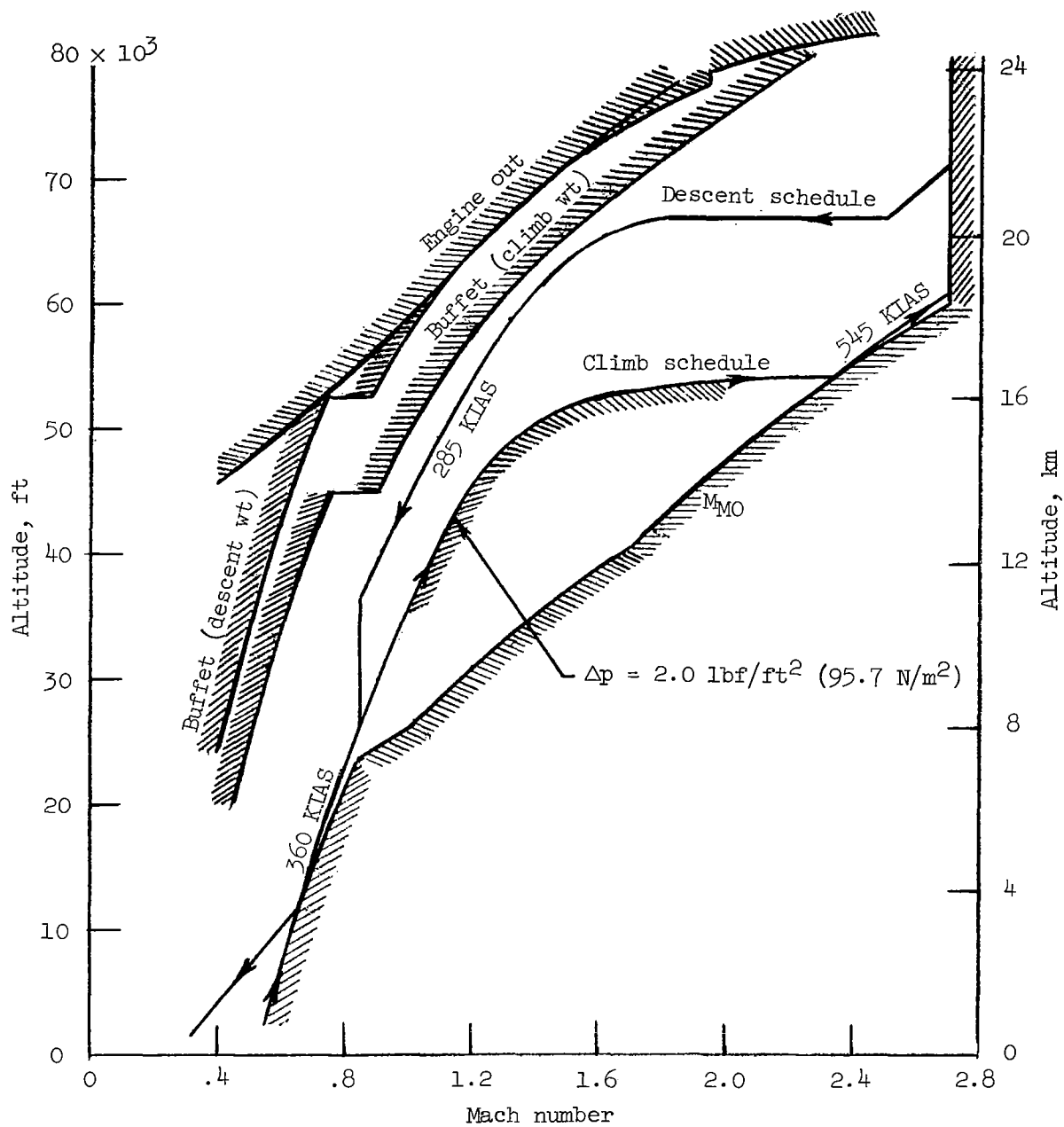
(e) LON oceanic. Low-population-density (sterile) areas shown.

Figure 7.- Continued.



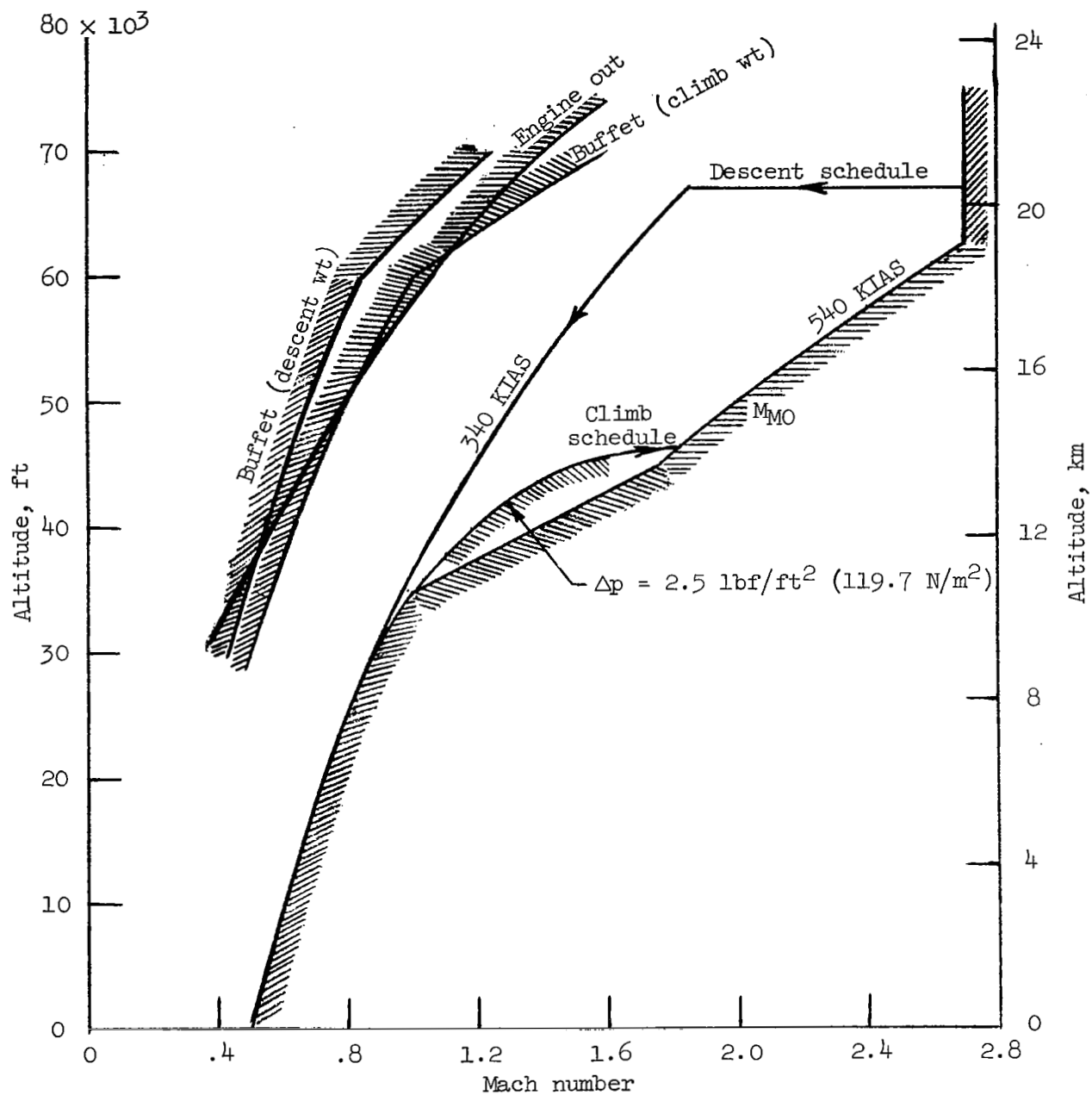
(a) Oceanic operations.

Figure 8.- Climb and descent schedules and flight limit boundaries. SST configuration A.



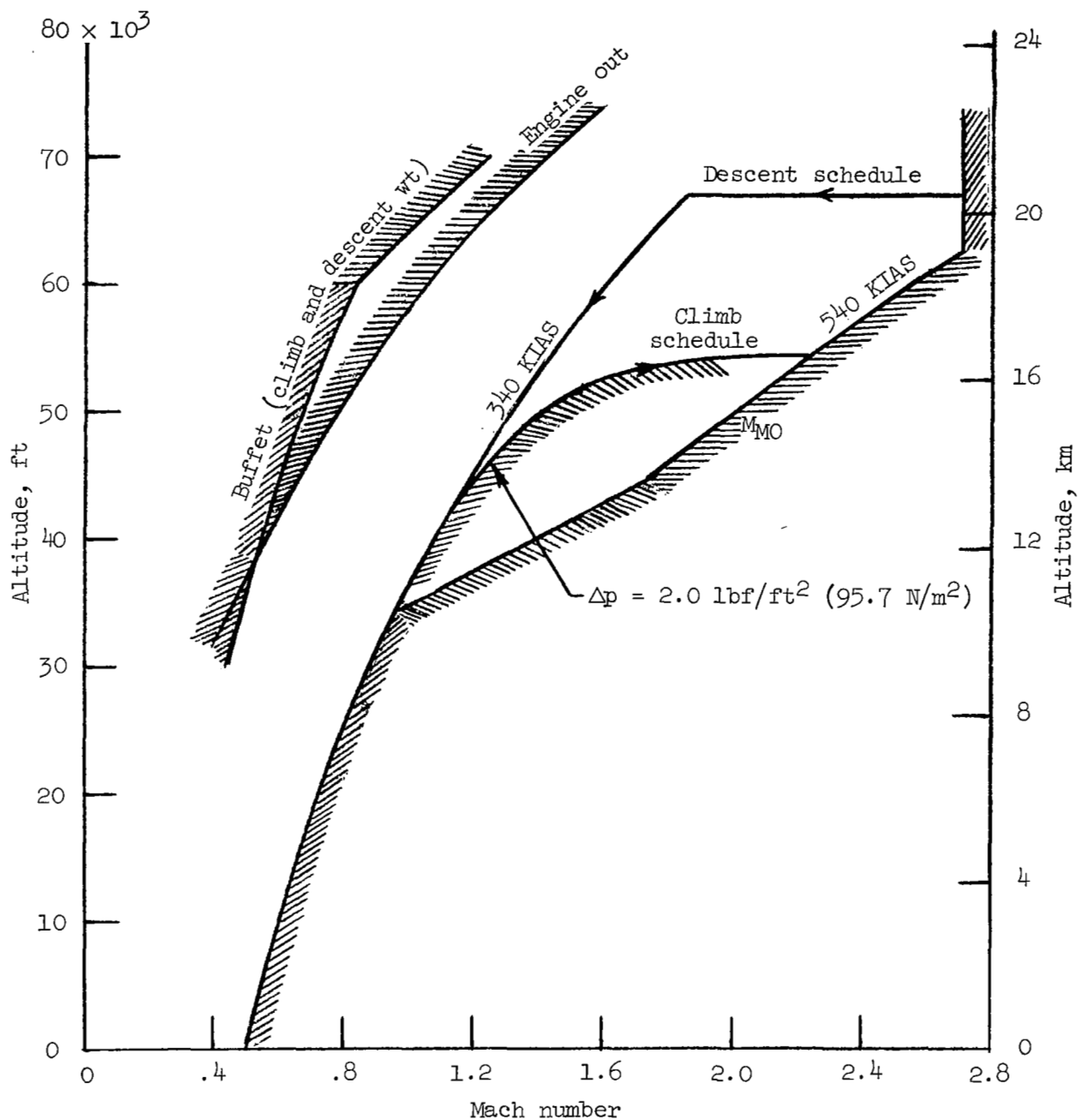
(b) Domestic operations.

Figure 8.- Concluded.



(a) Oceanic operations.

Figure 9.- Climb and descent schedules and flight limit boundaries. SST configuration B.



(b) Domestic operations.

Figure 9.- Concluded.

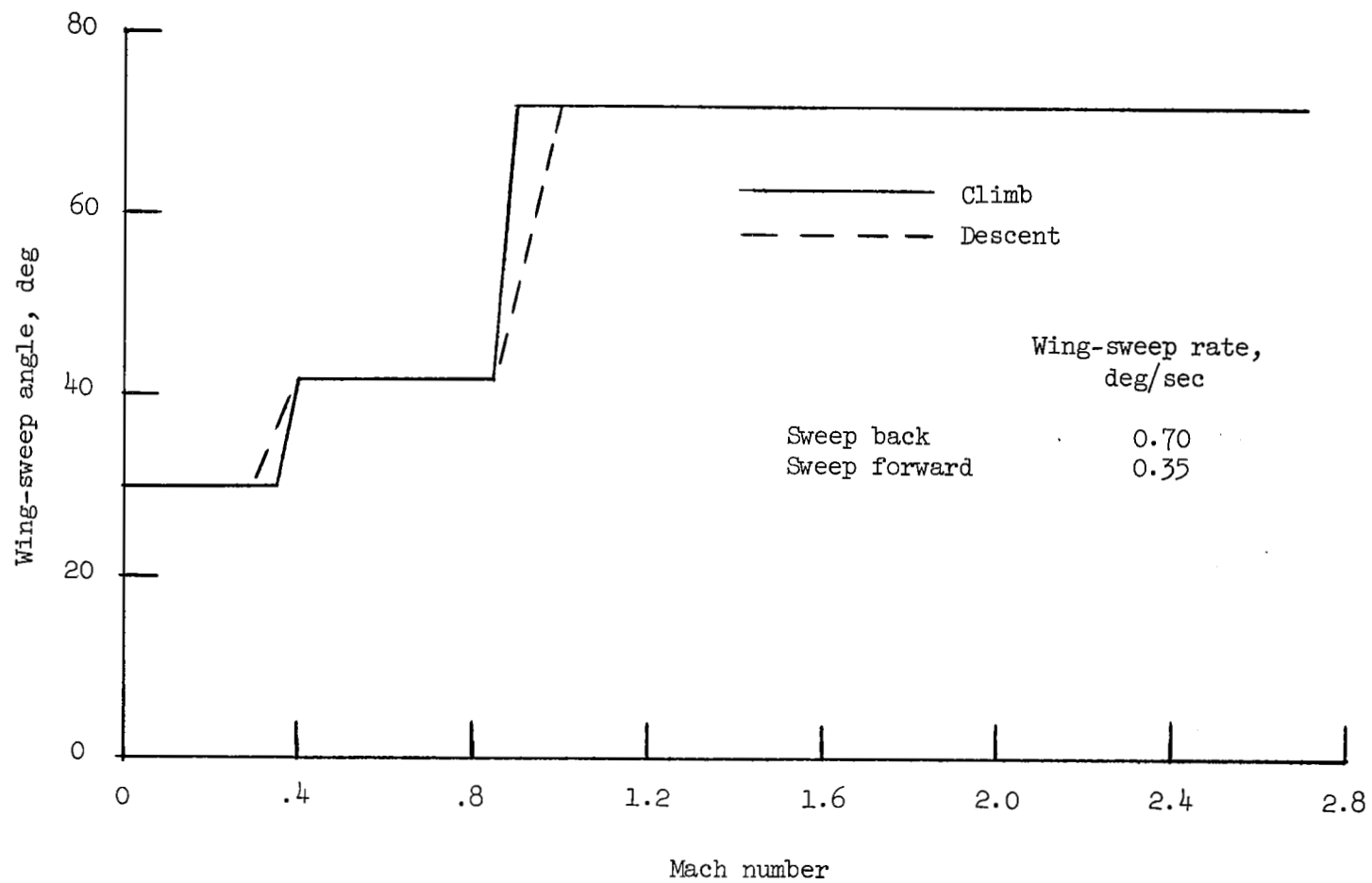
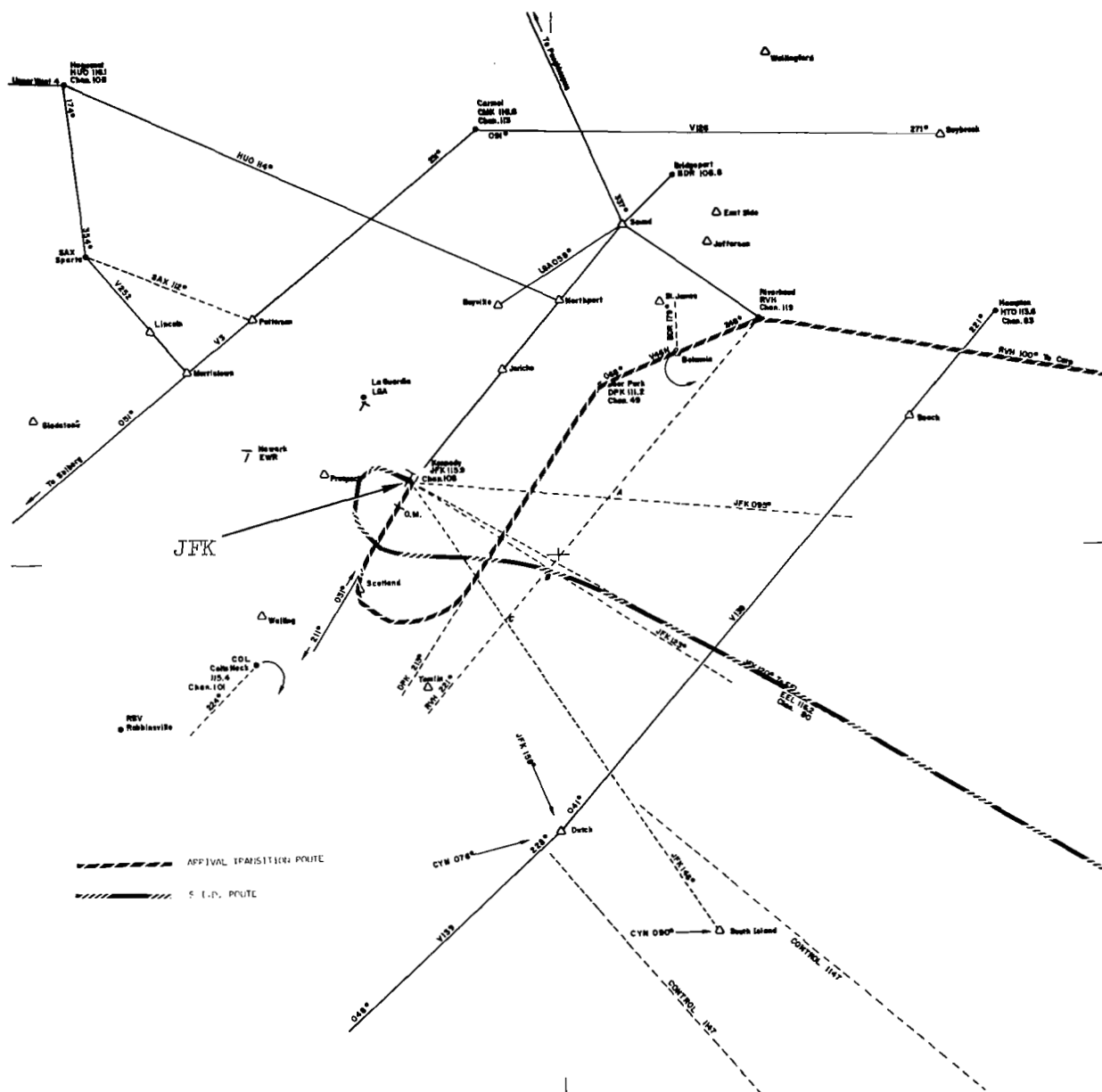
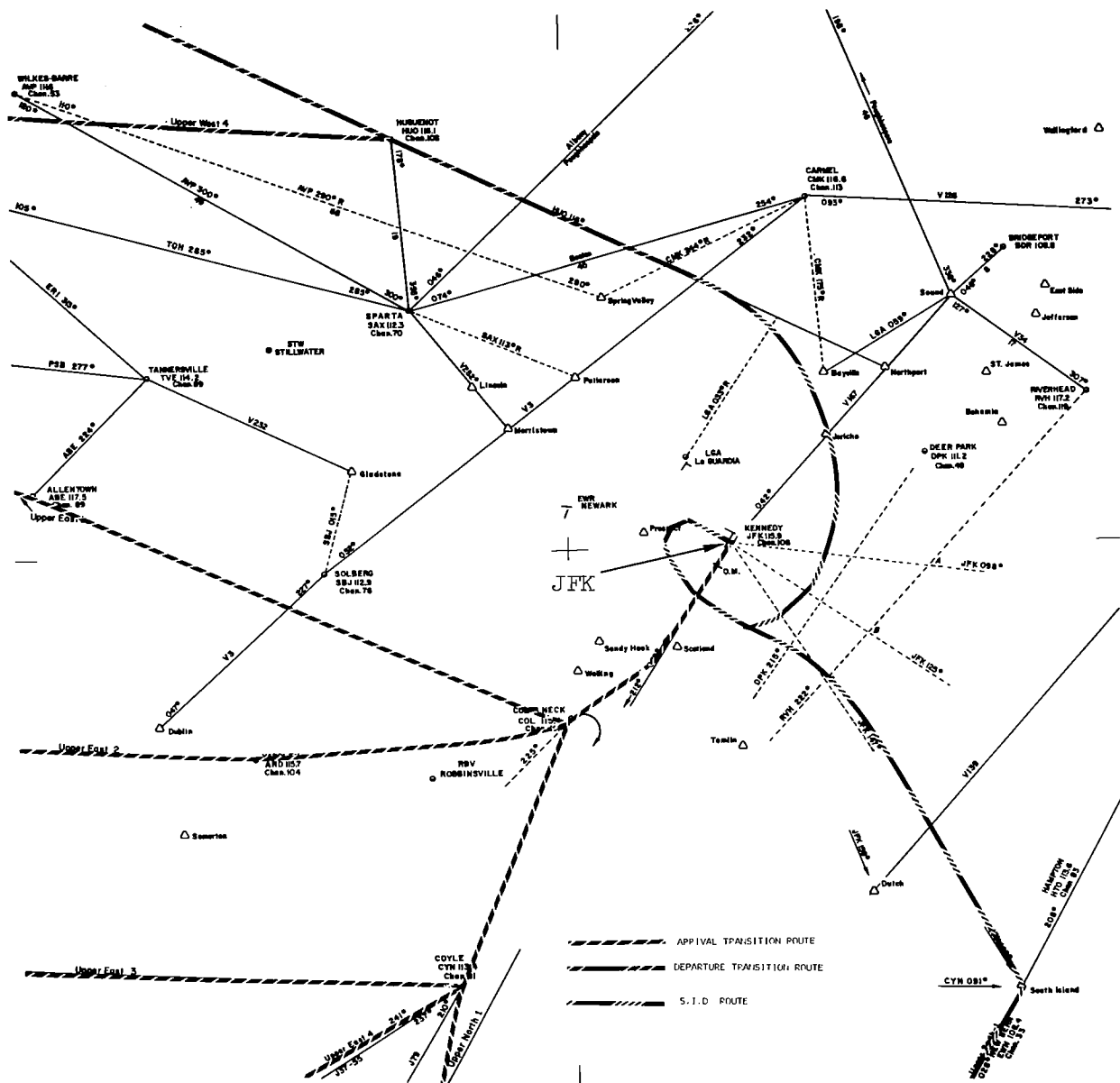


Figure 10.- Manual wing-sweep program for SST configuration A.



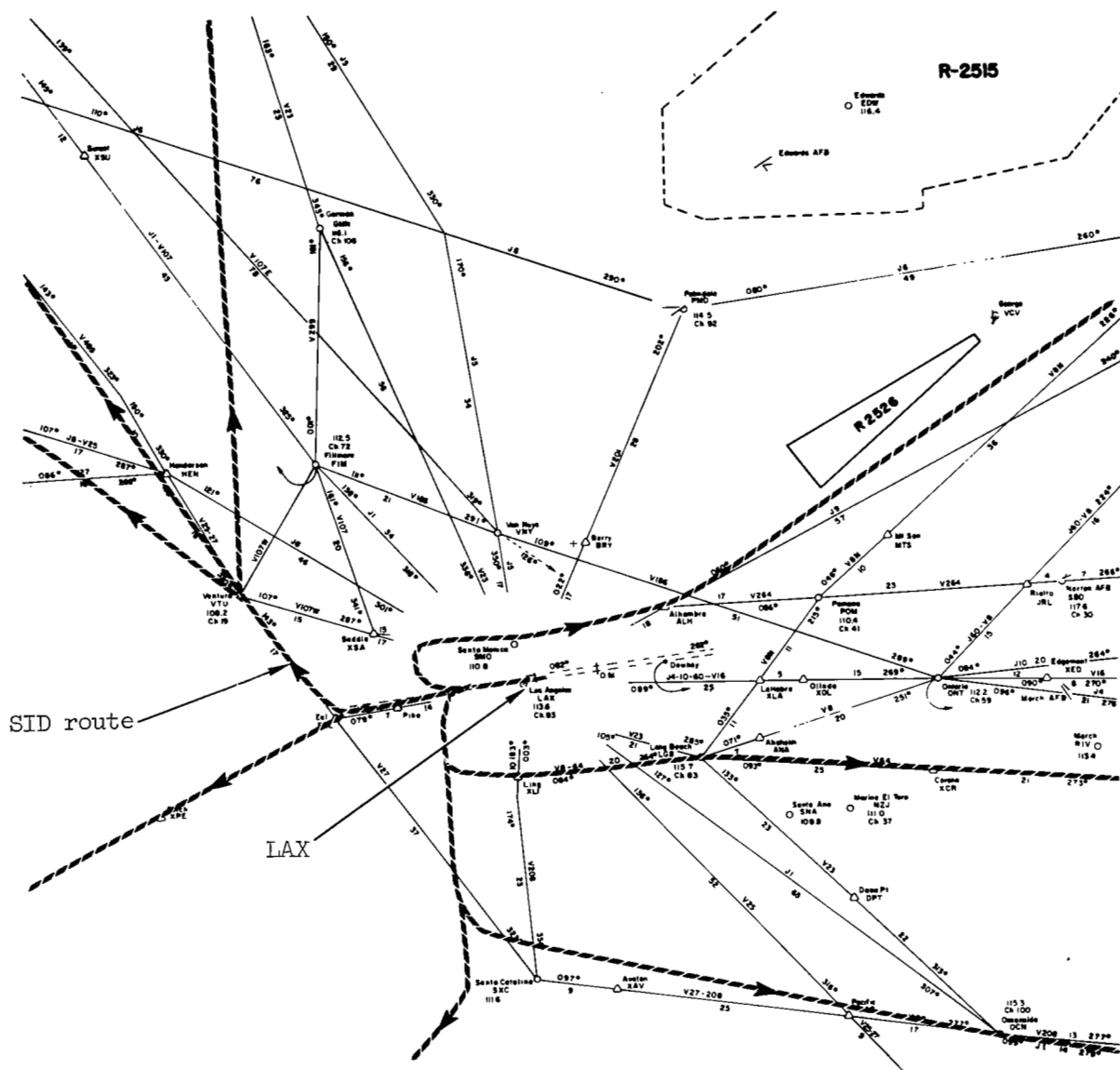
(a) JFK oceanic operations.

Figure 11.- Standard instrument departure and terminal arrival routes. JFK and LAX areas.



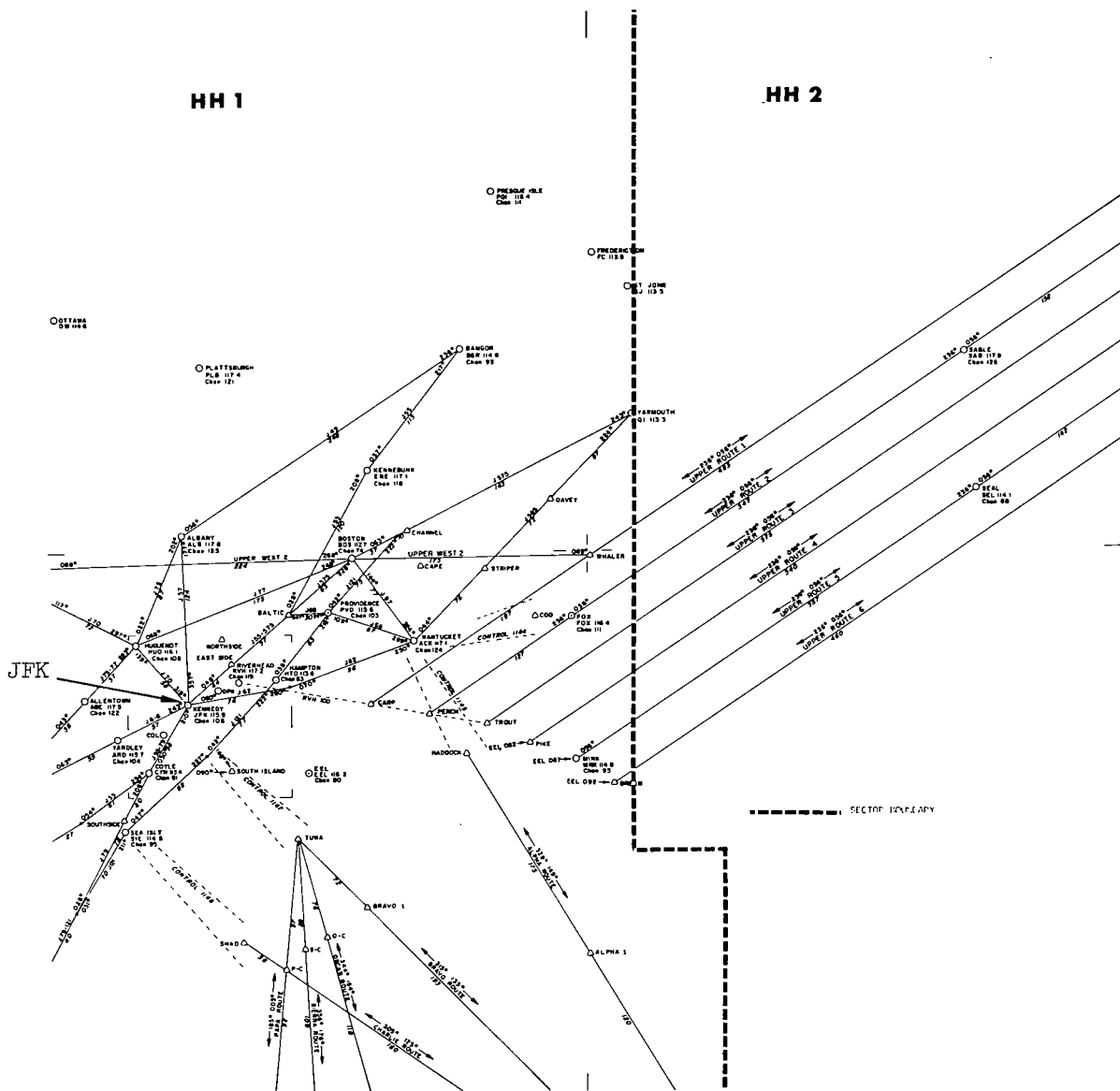
(b) JFK domestic operations.

Figure 11.- Continued.



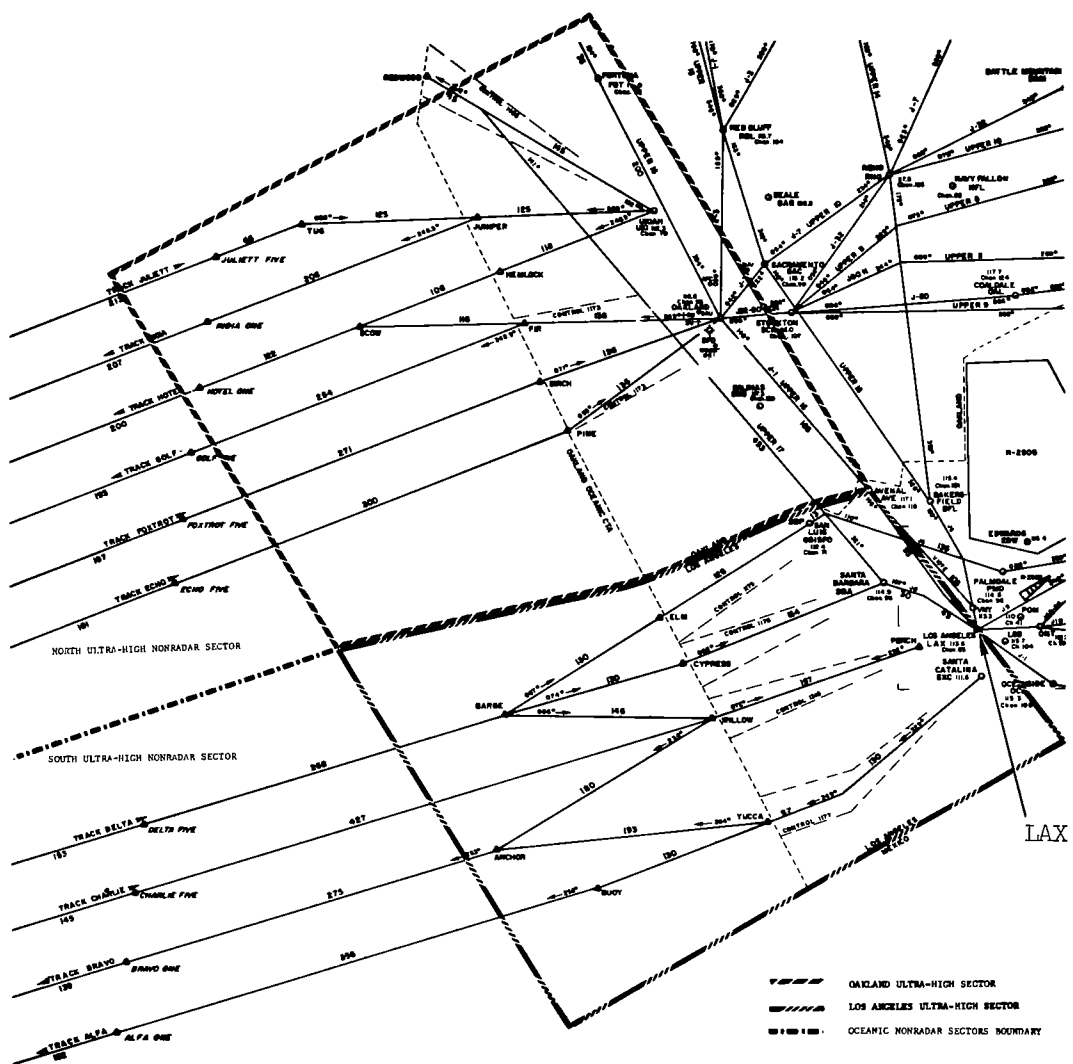
(c) LAX departure operations.

Figure 11.- Continued.



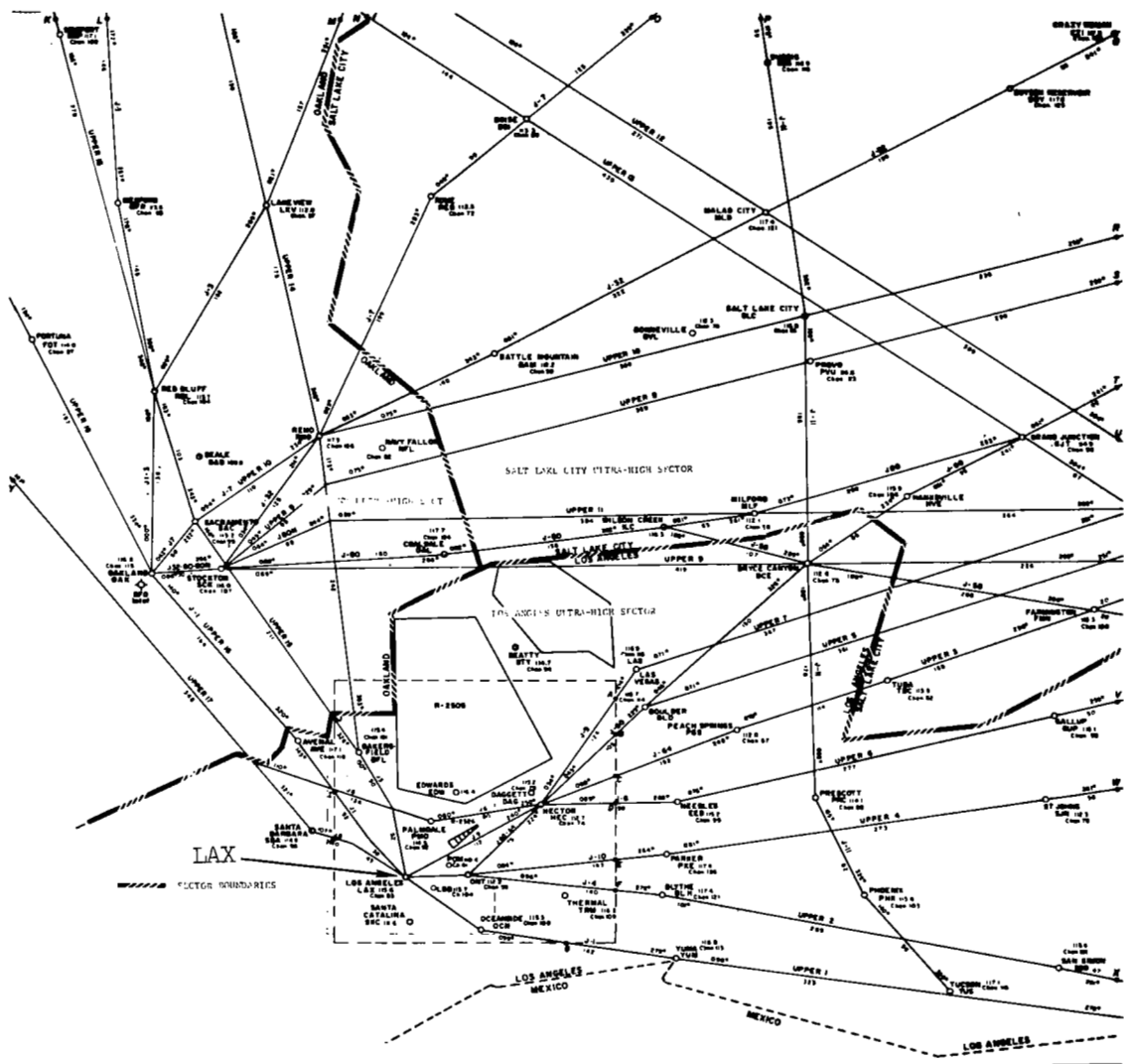
(a) JFK oceanic operations.

Figure 12.- Sectorization of airspace above about FL400 for control purposes. (Ultrahigh sectors.)



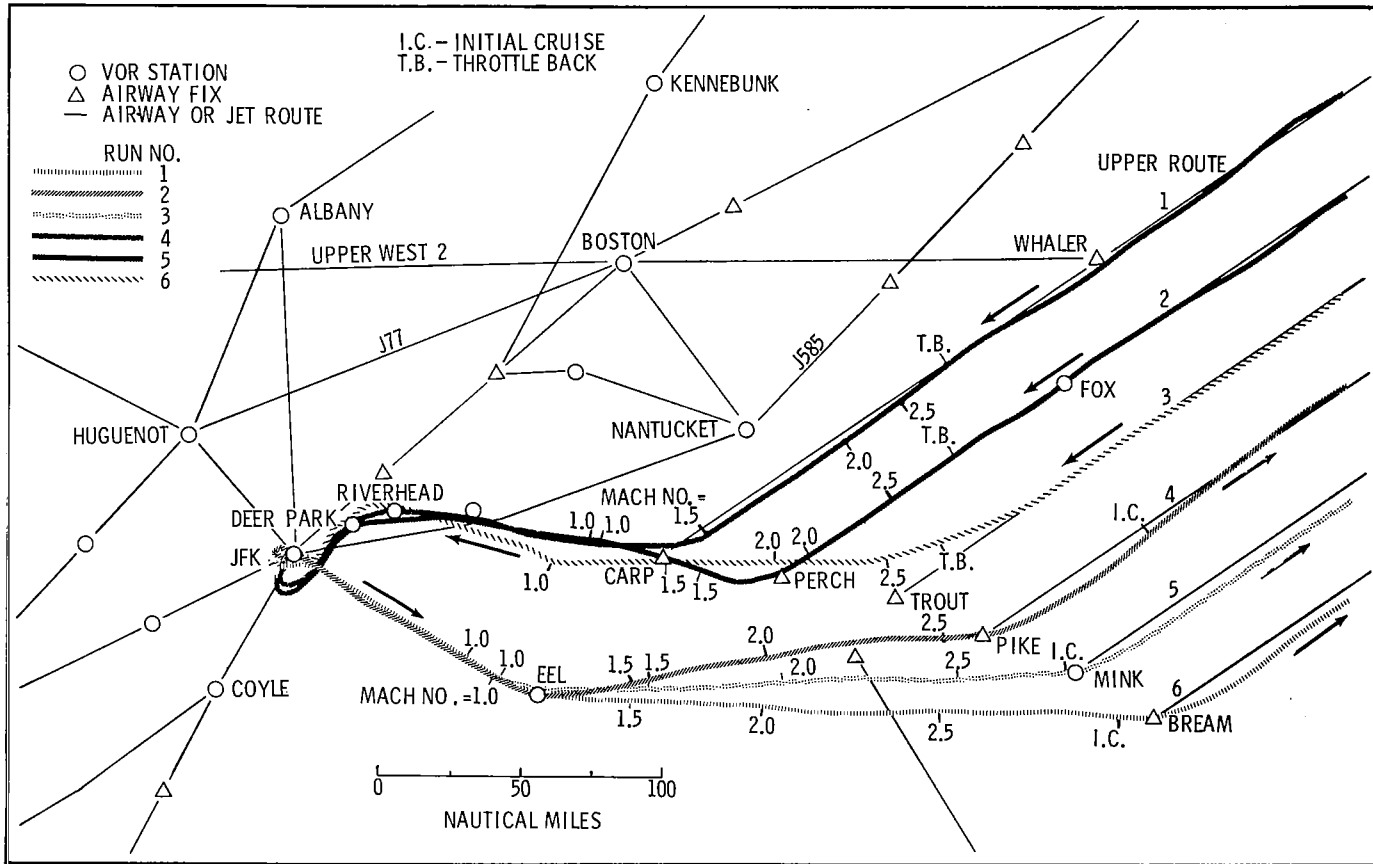
(c) LAX oceanic operations.

Figure 12.- Continued.



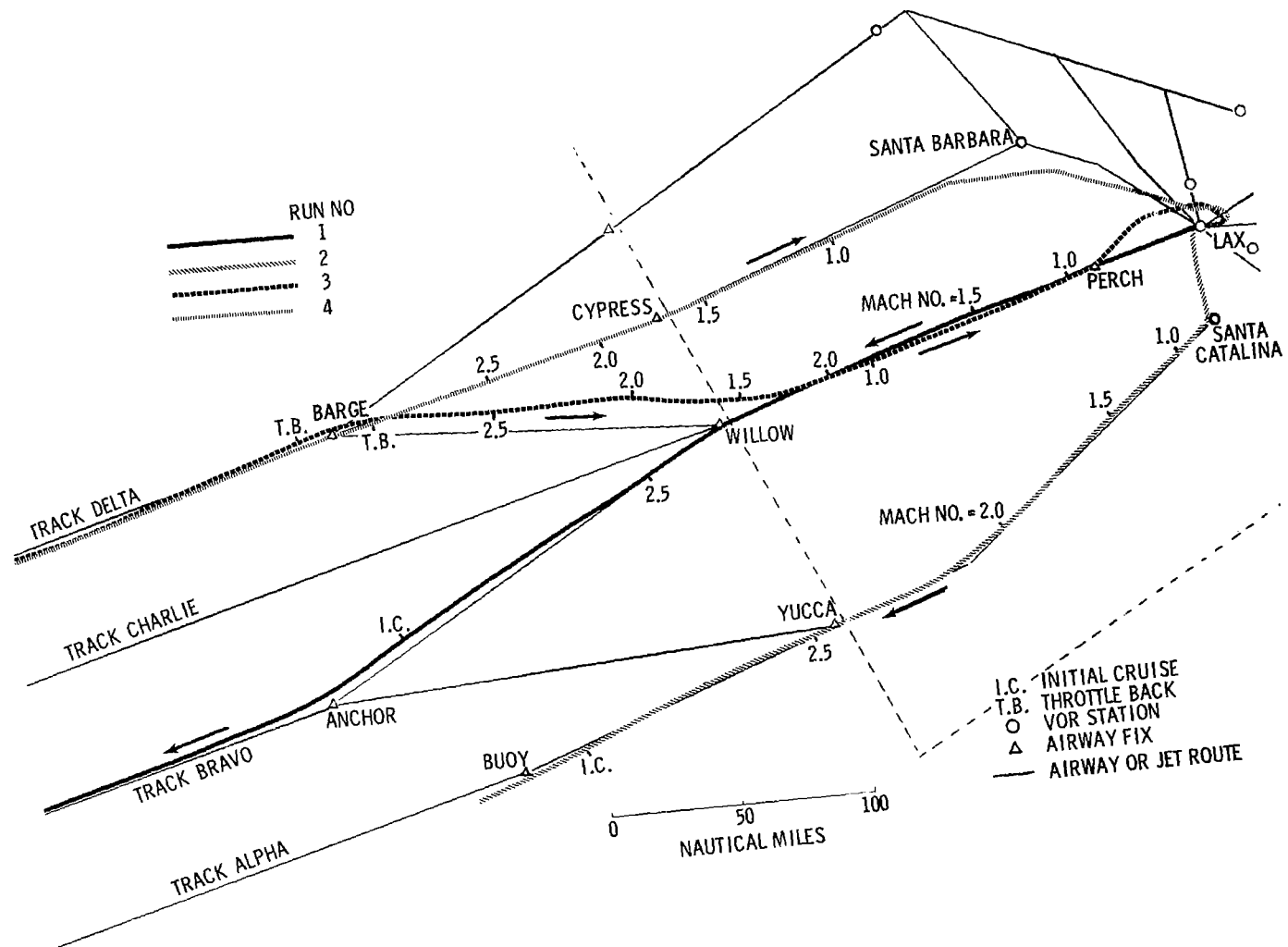
(d) LAX domestic operations.

Figure 12.- Concluded.



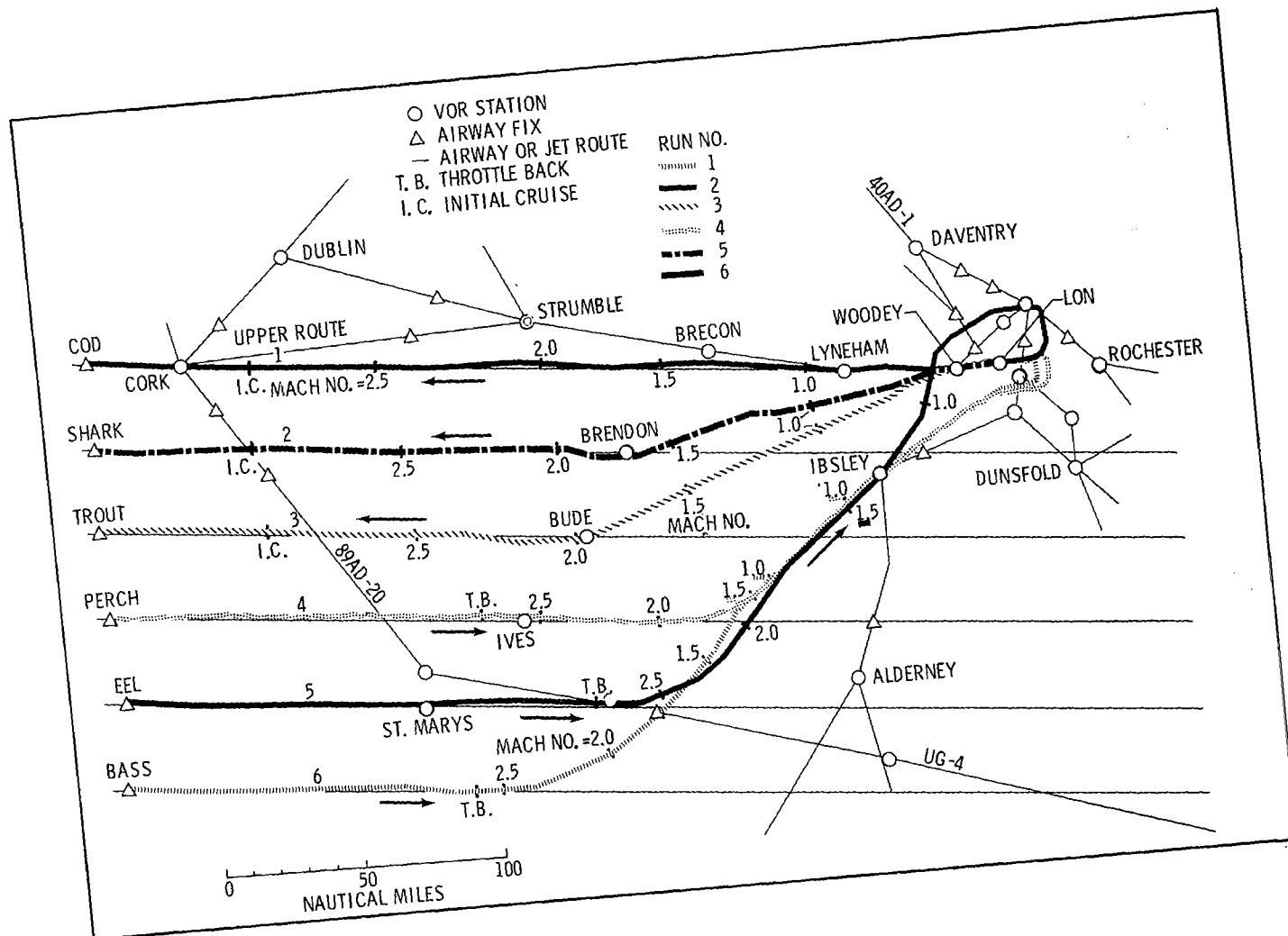
(a) JFK oceanic departures and arrivals.

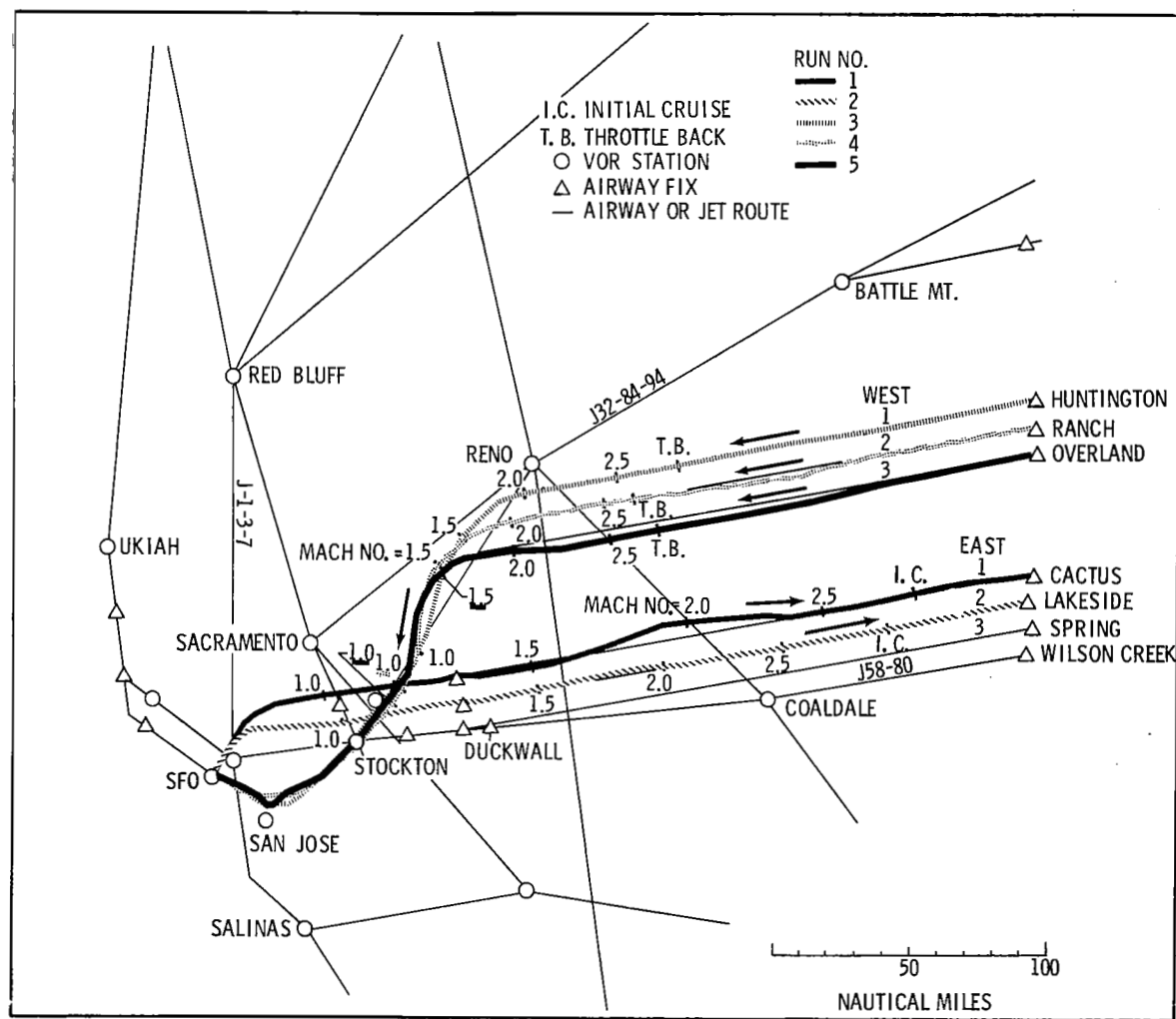
Figure 13.- Examples of ground tracks for departure and arrival operations of SST in ATC systems conceived for the future.



(c) LAX oceanic departures and arrivals.

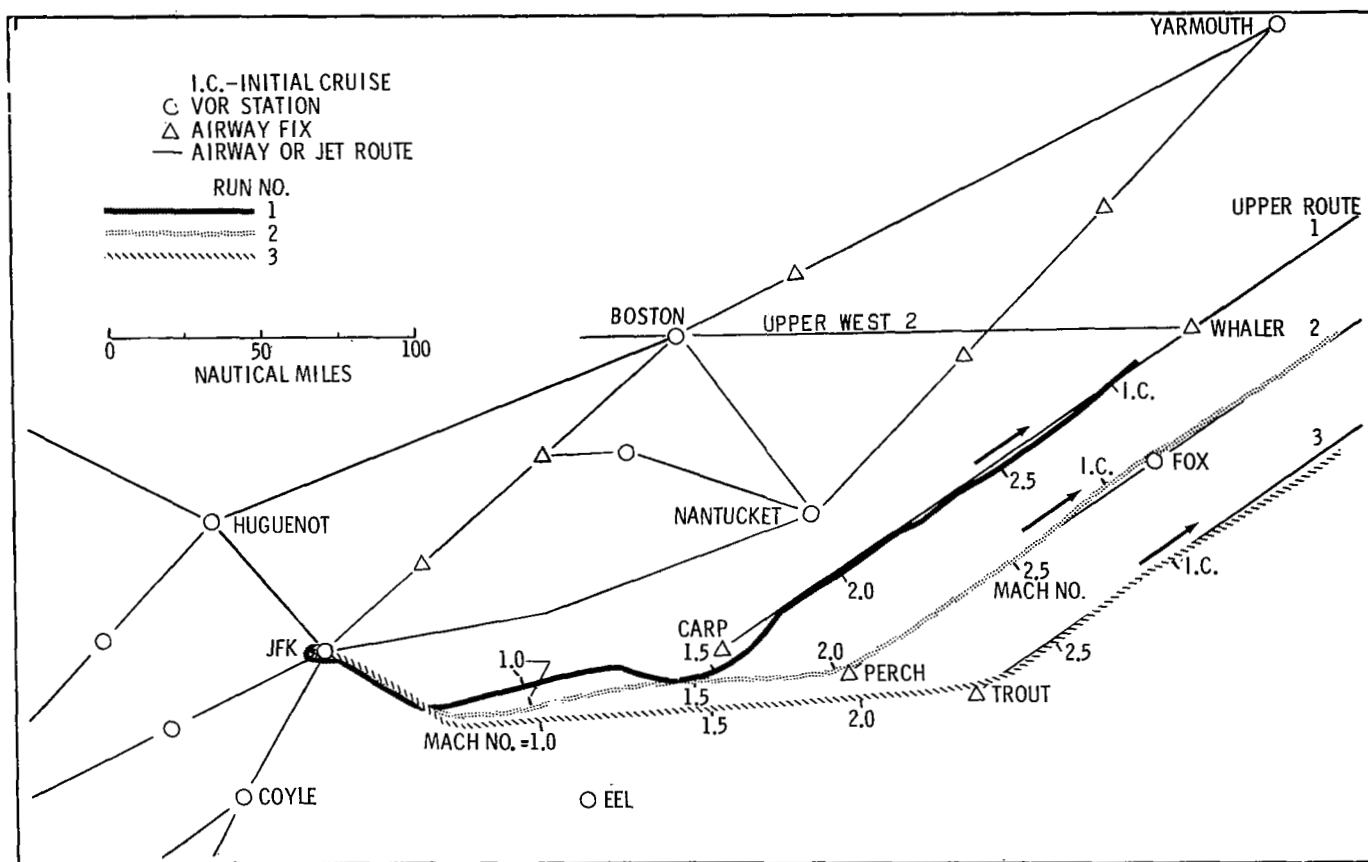
Figure 13.- Continued.





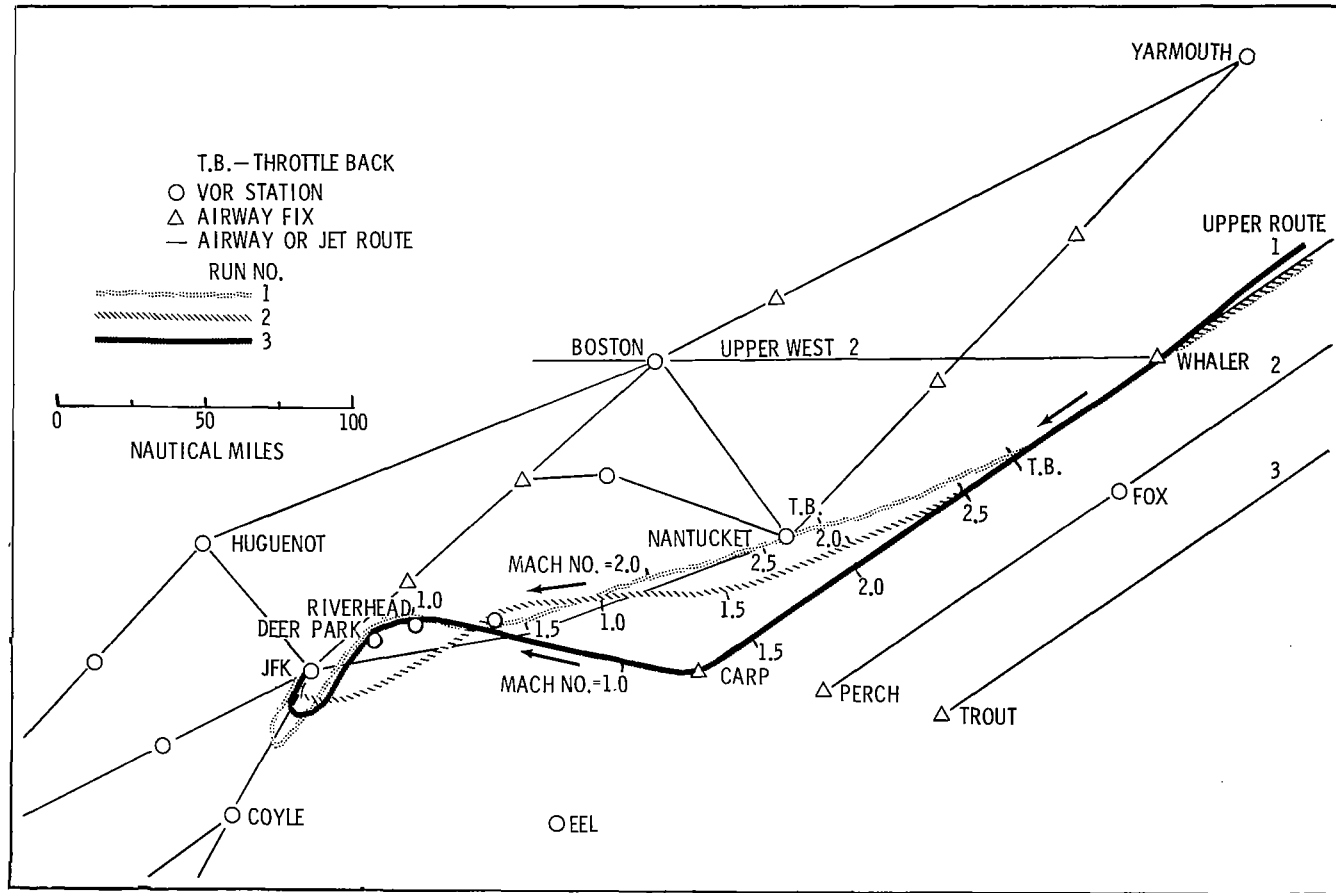
(f) SFO domestic departures and arrivals.

Figure 13.- Continued.



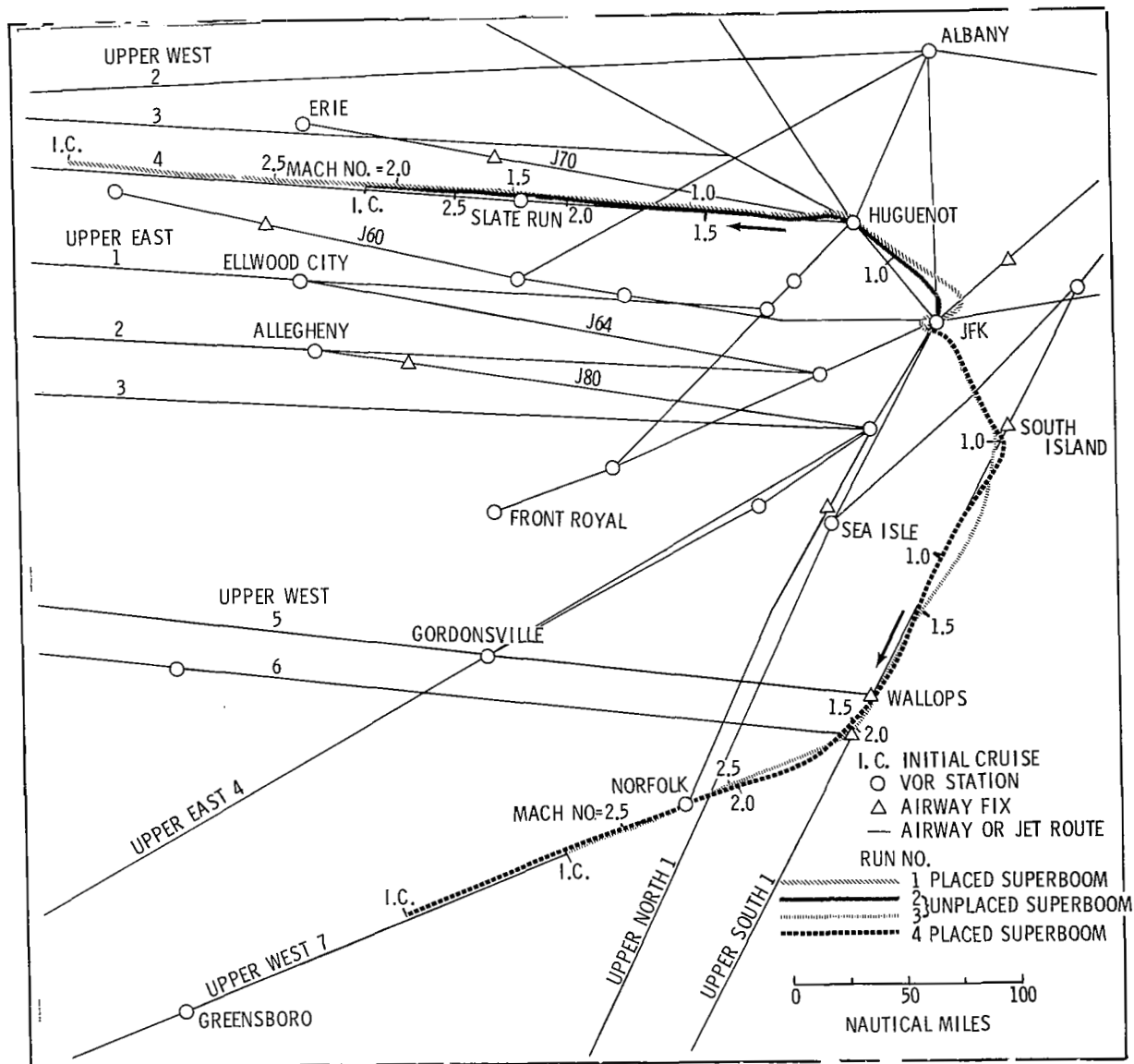
(g) JFK oceanic departures. Two-way 3-track system.

Figure 13.- Continued.



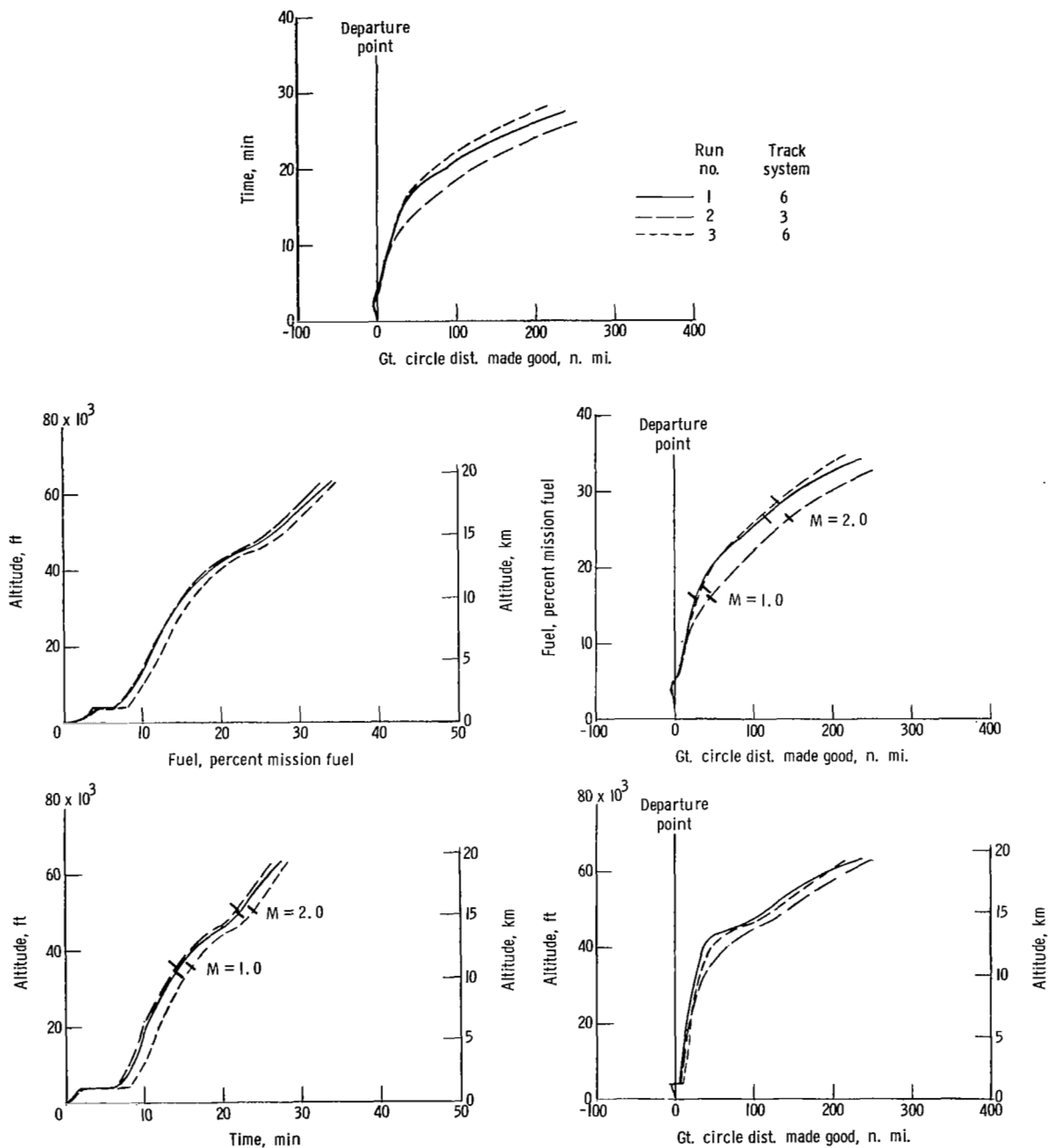
(h) JFK oceanic arrivals. Two-way 3-track system.

Figure 13.- Continued.



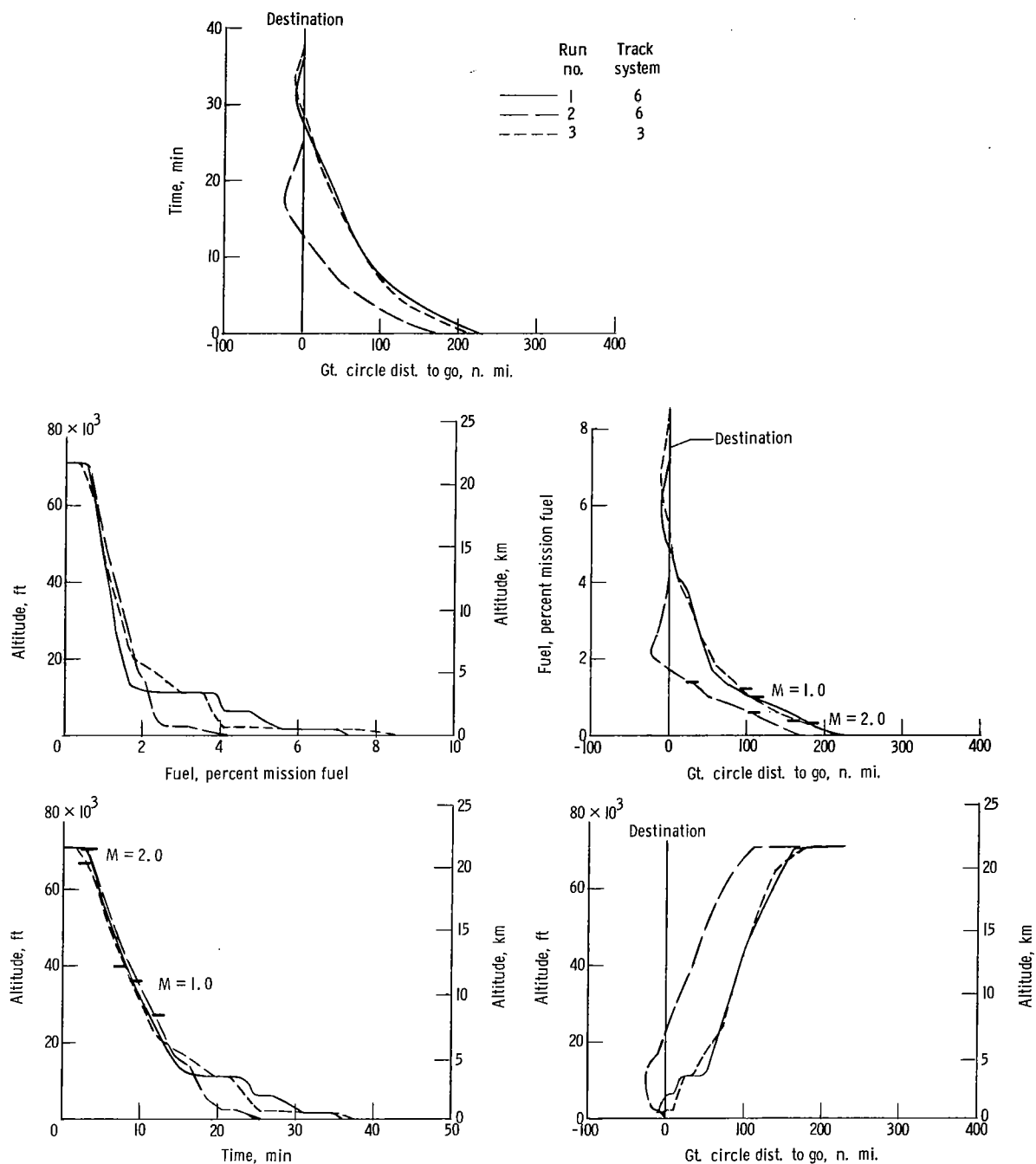
(i) JFK domestic departures. Placed and unplaced superboom operations.

Figure 13.- Concluded.



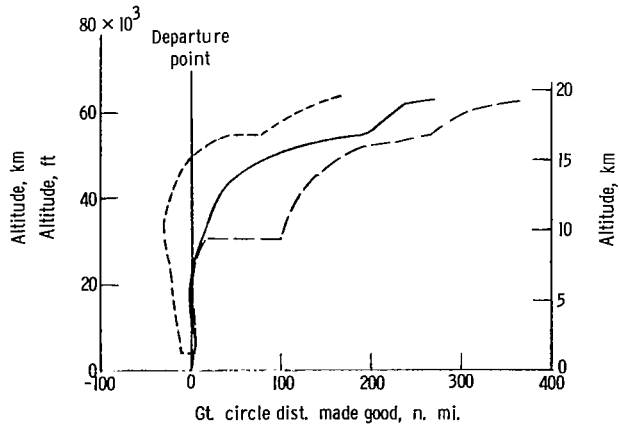
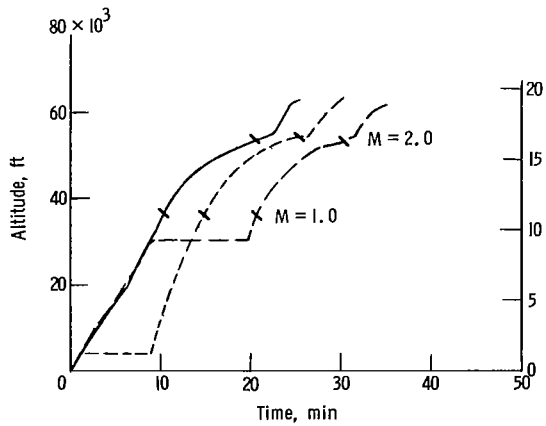
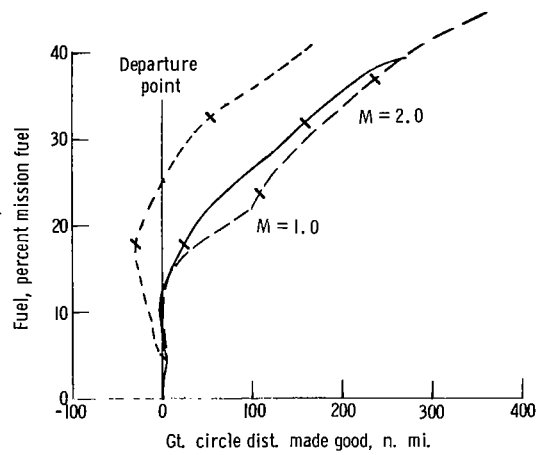
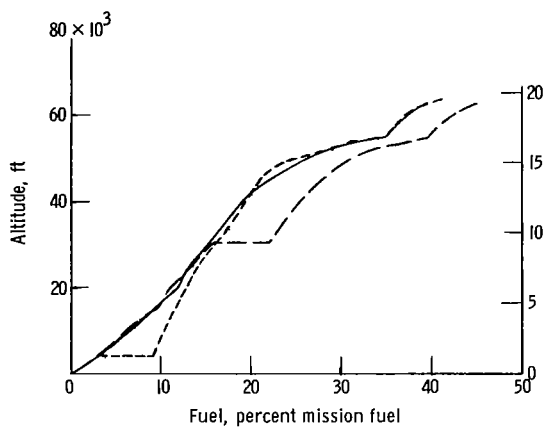
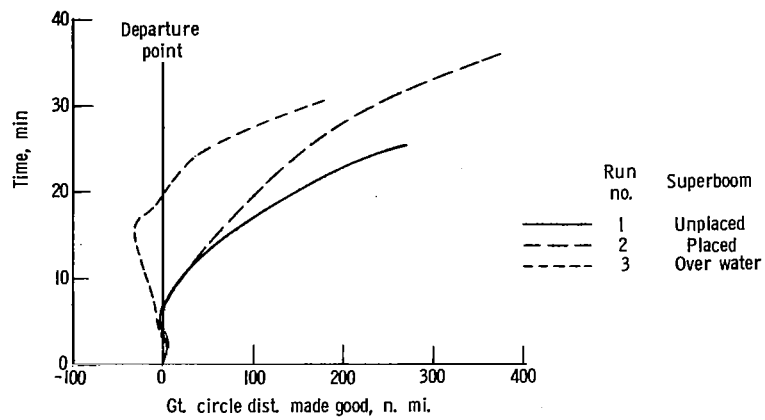
(a) JFK oceanic departures.

Figure 14.- Examples of altitude, fuel, time, and distance relationships for departure and arrival operations of the SST in ATC systems conceived for the future.



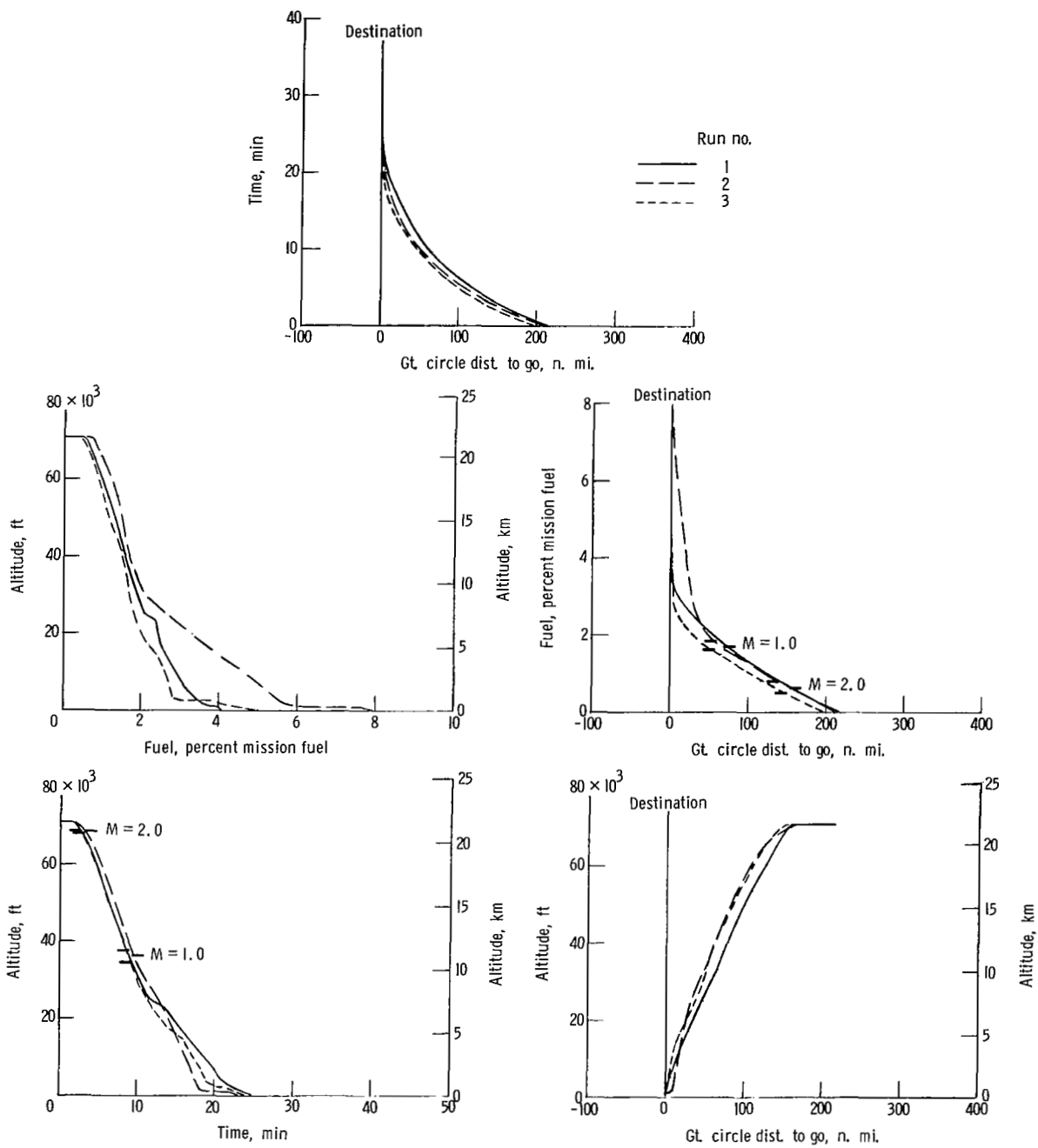
(b) JFK oceanic arrivals.

Figure 14.- Continued.



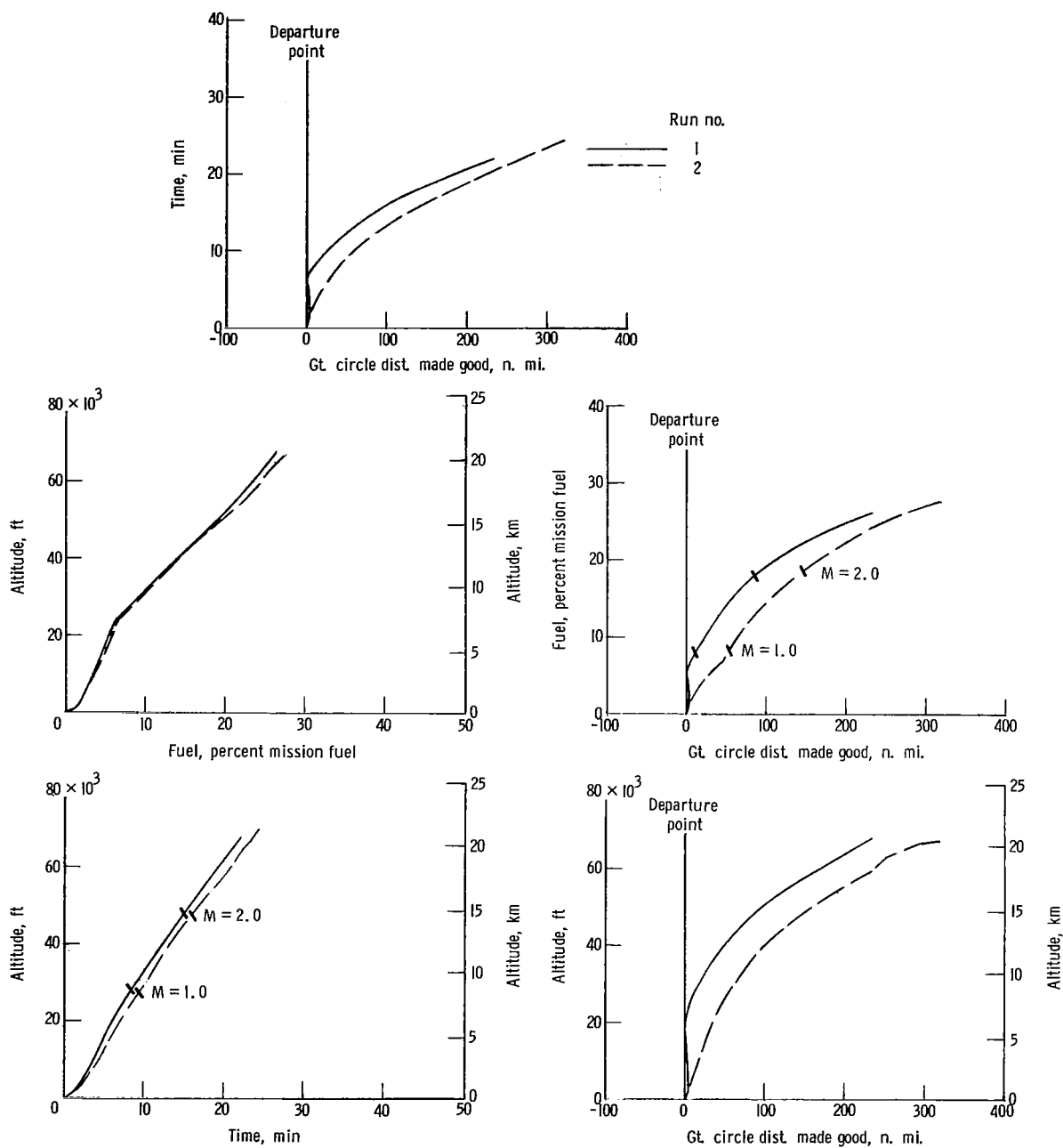
(c) JFK domestic departures.

Figure 14.- Continued.



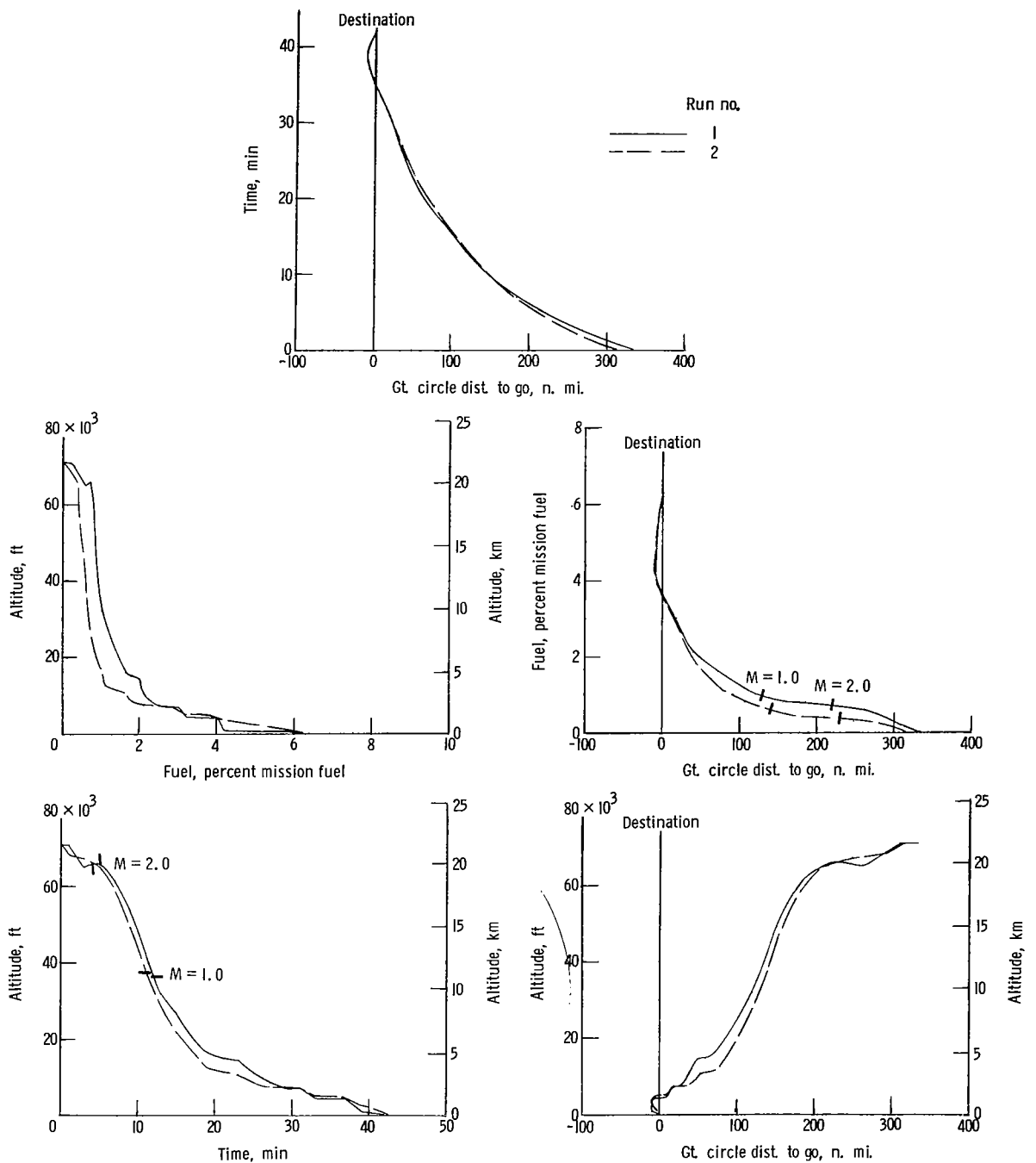
(d) JFK domestic arrivals.

Figure 14.- Continued.



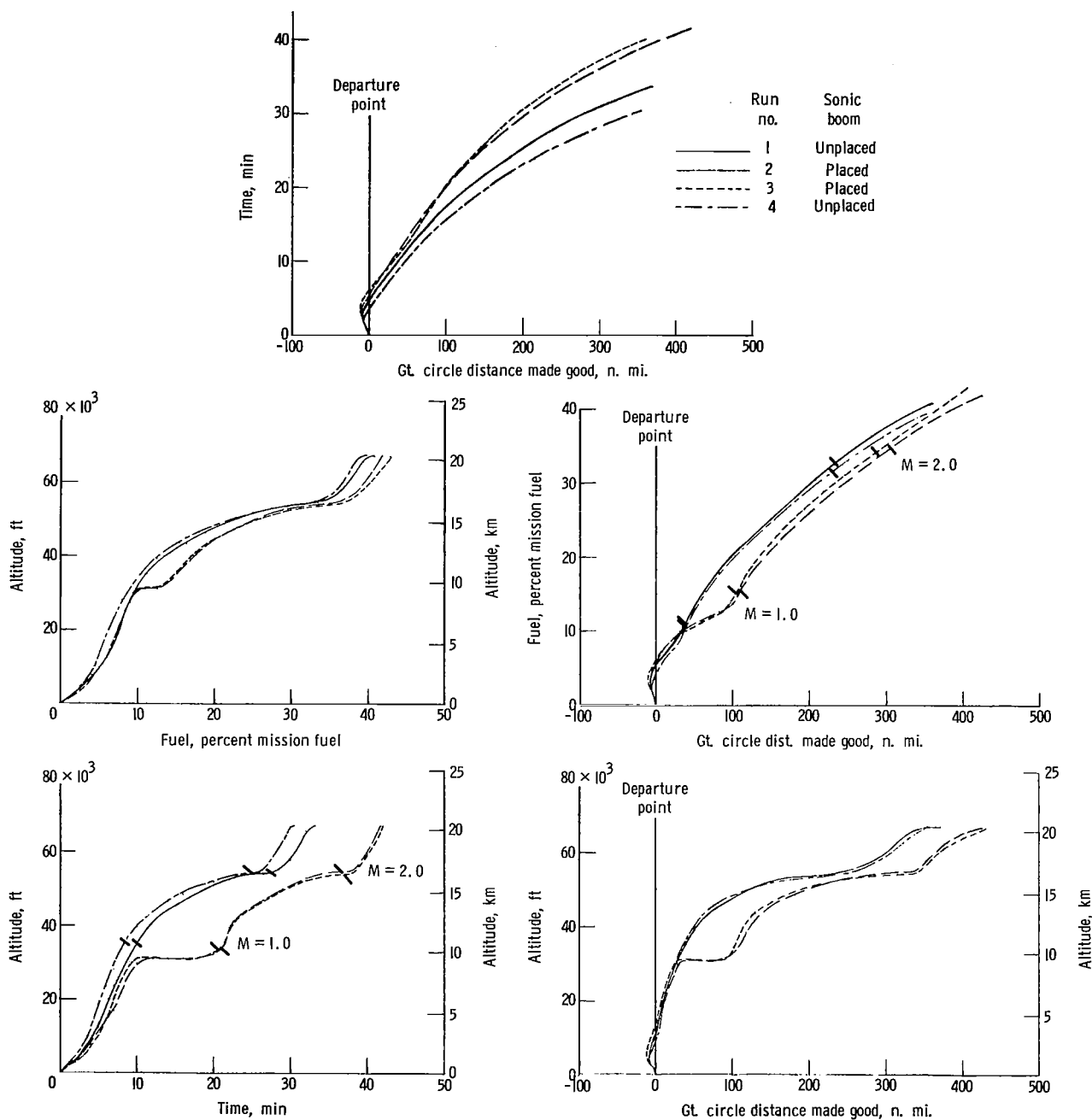
(e) LAX oceanic departures.

Figure 14.- Continued.



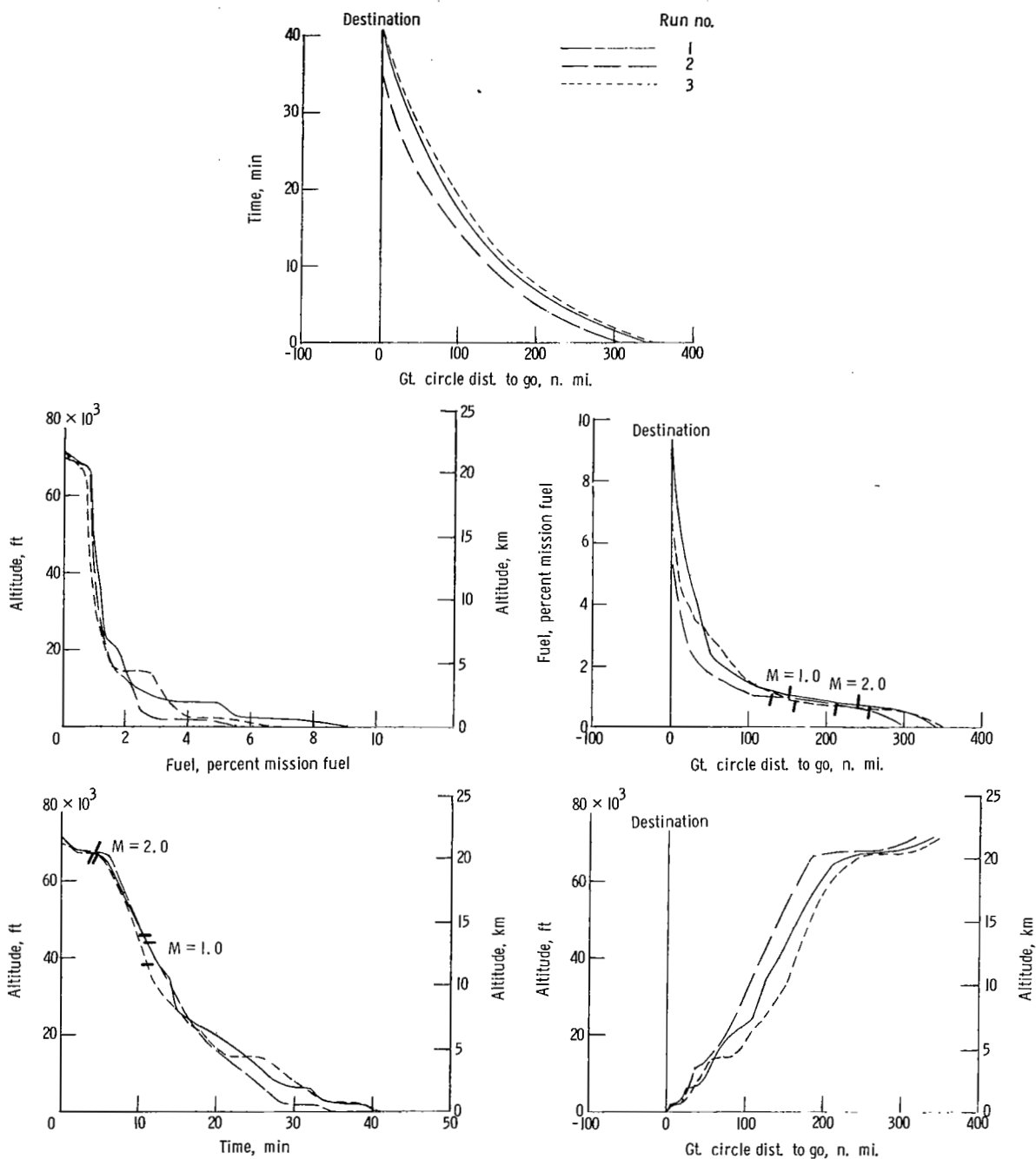
(f) LAX oceanic arrivals.

Figure 14.- Continued.



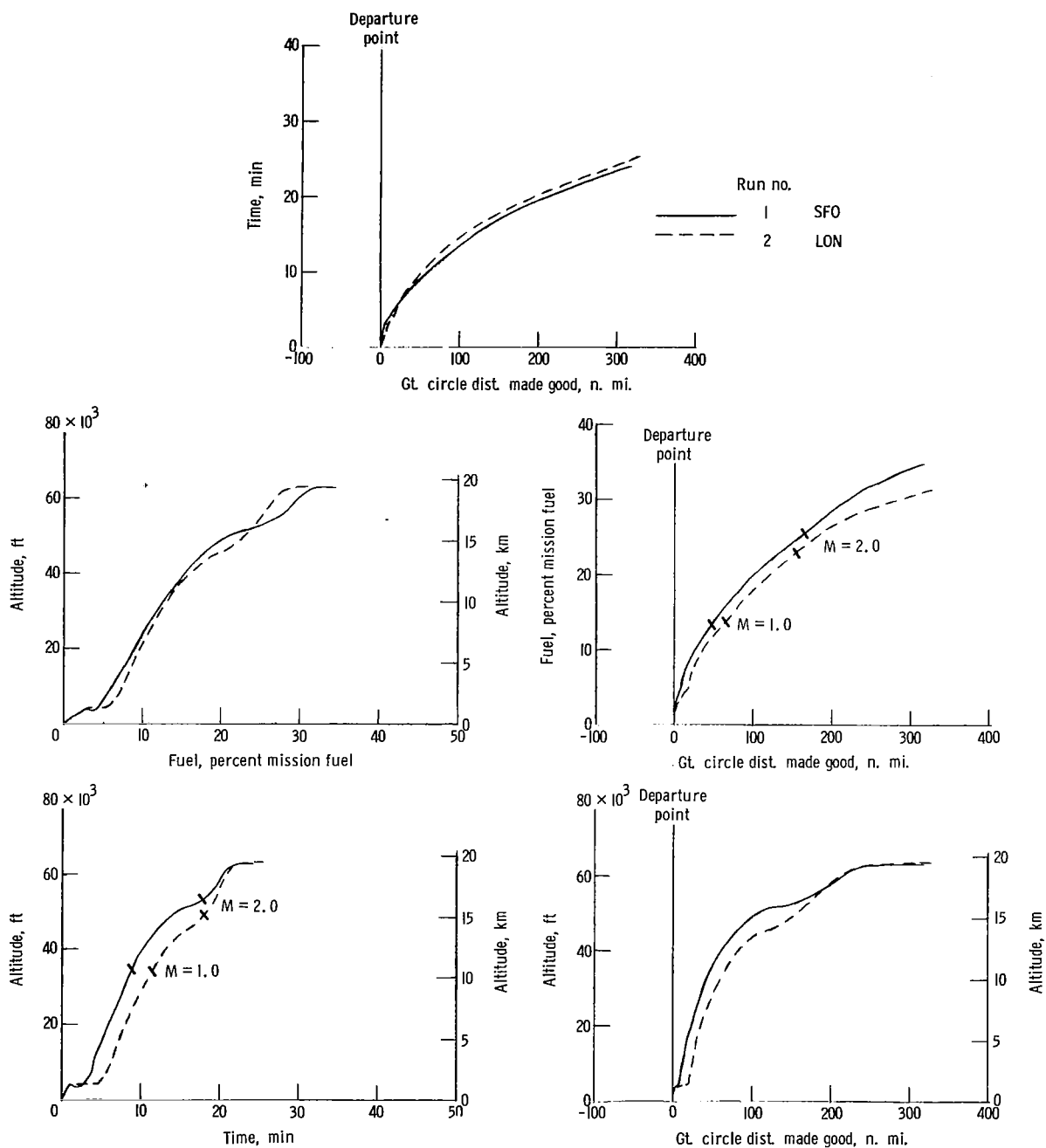
(g) LAX domestic departures.

Figure 14.- Continued.



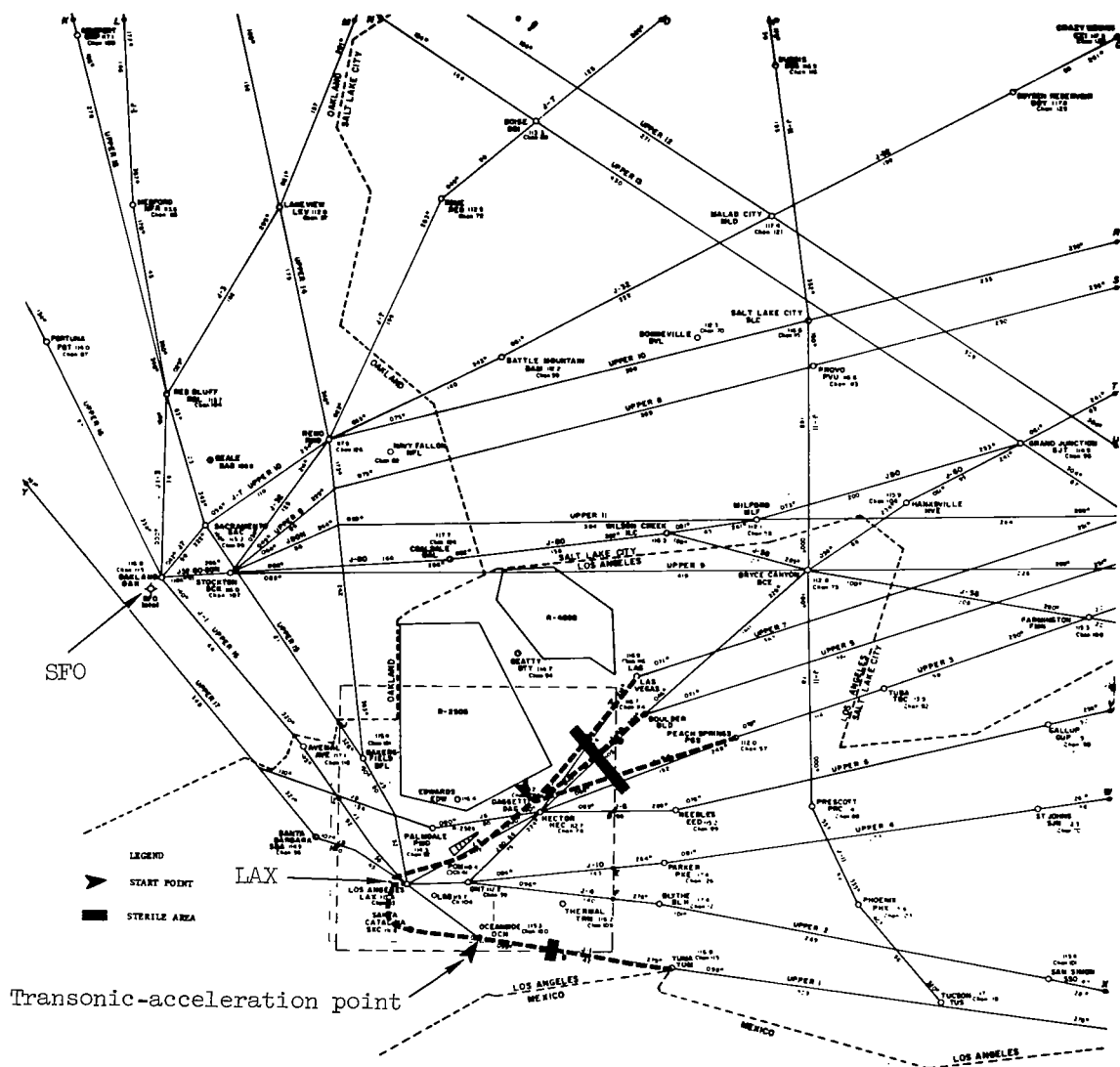
(h) LAX domestic arrivals.

Figure 14.- Continued.



(i) LON oceanic and SFO domestic departures.

Figure 14.- Continued.



(b) LAX area. Low-population-density (sterile) area shown.

Figure 15.- Concluded.

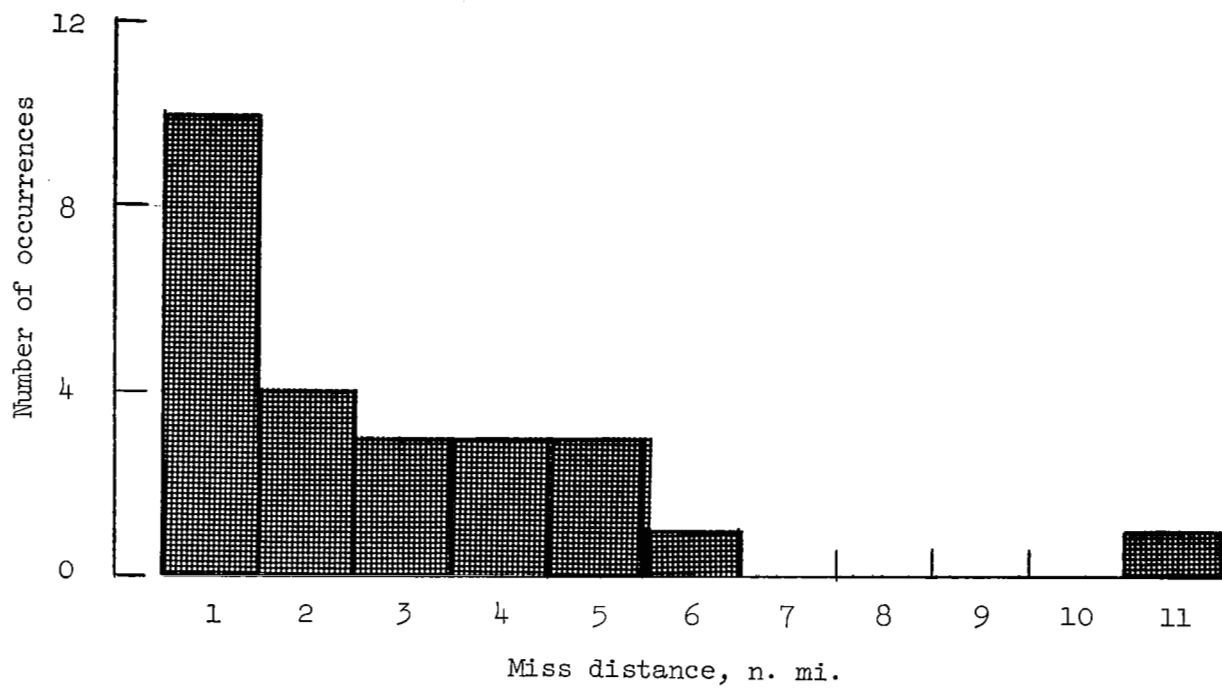


Figure 16.- Miss distances in 25 flights of placement of superboom. Operations in JFK and LAX areas.

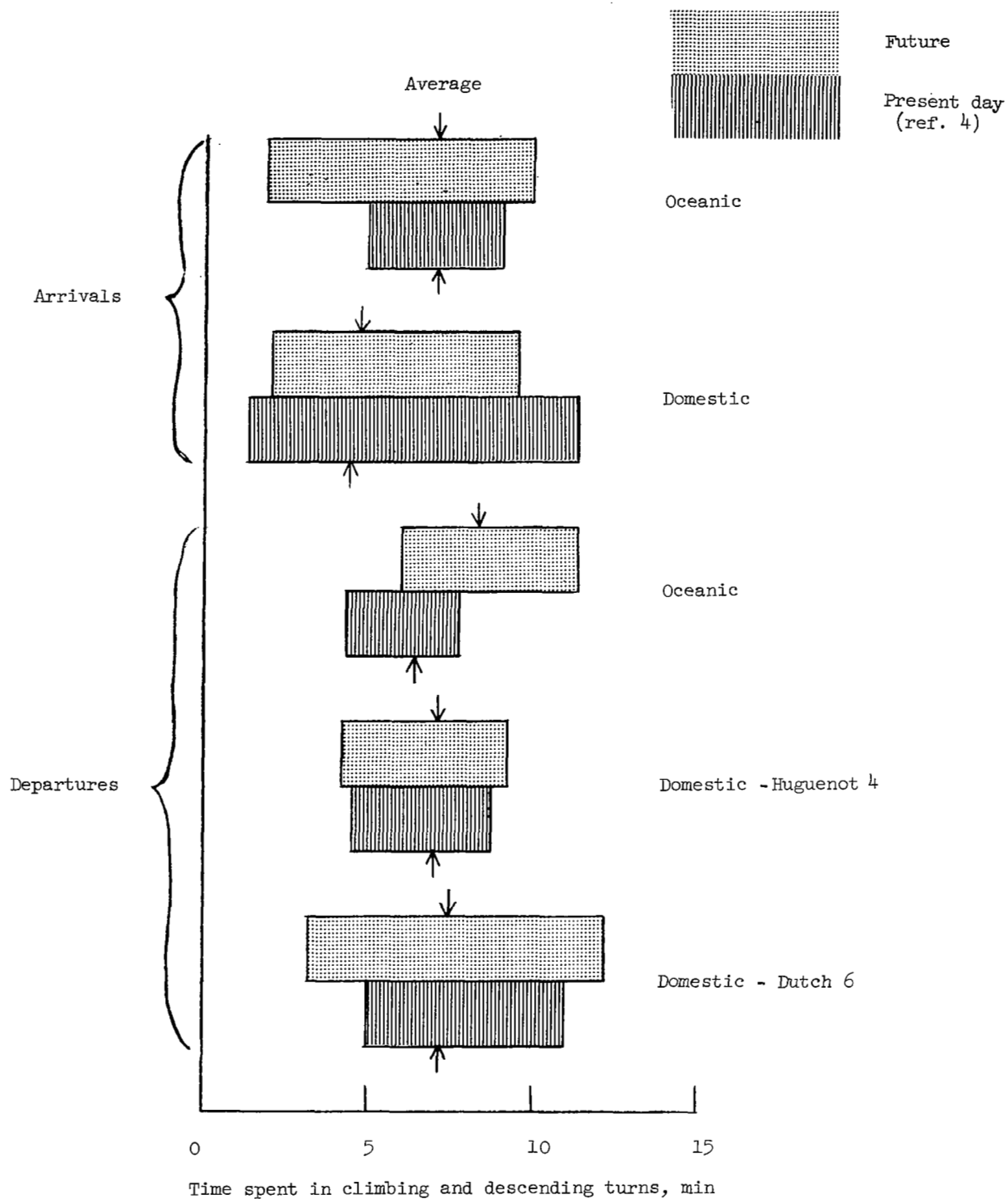


Figure 17.- Time spent in climbing and descending turns. Future and present-day ATC systems. JFK oceanic and domestic operations.

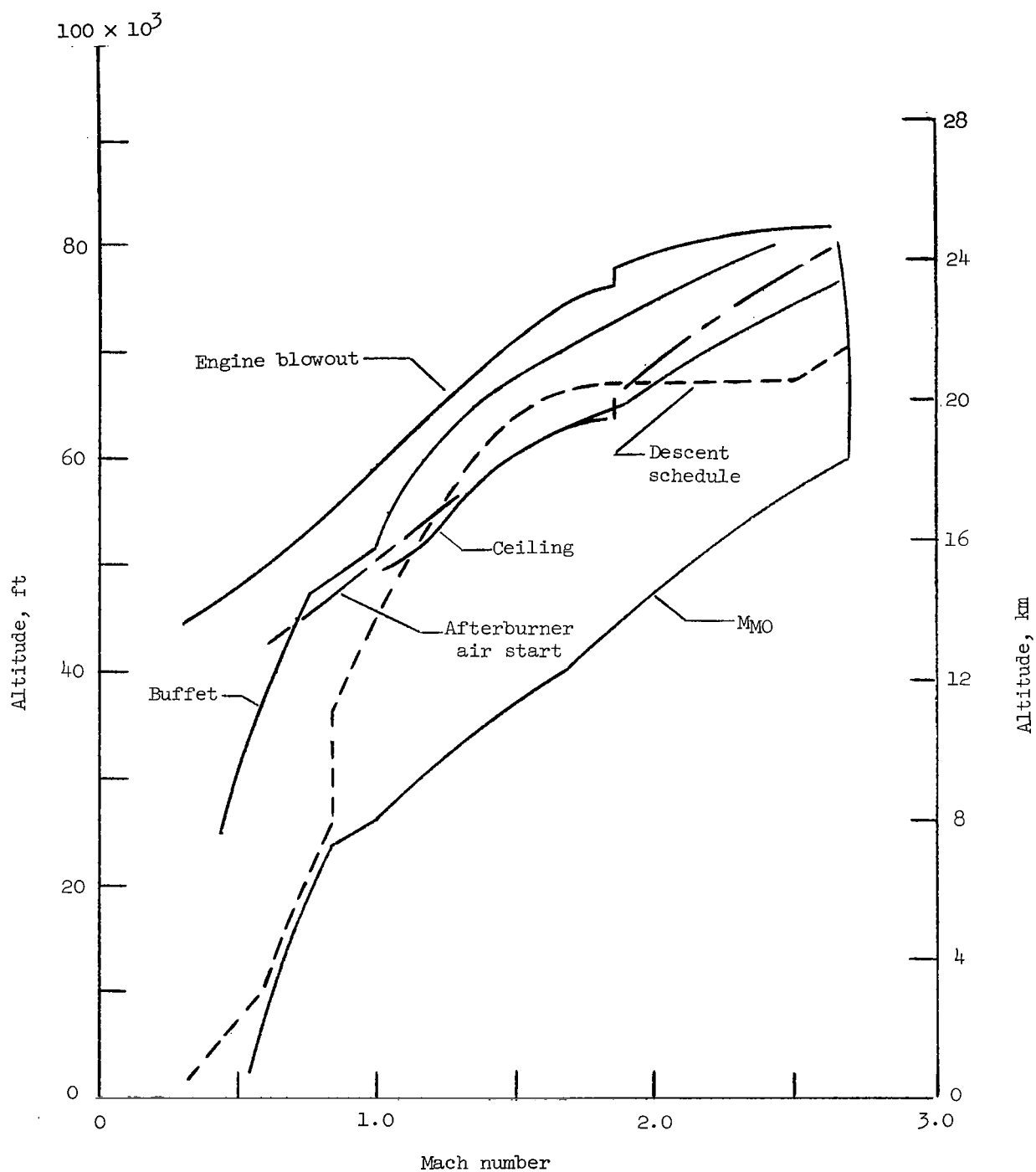


Figure 18.- Relationship of descent schedule and airplane operating boundaries. SST configuration A. Maximum Δp in descent is 1.5 pounds force per square foot (71.8 N/m^2).

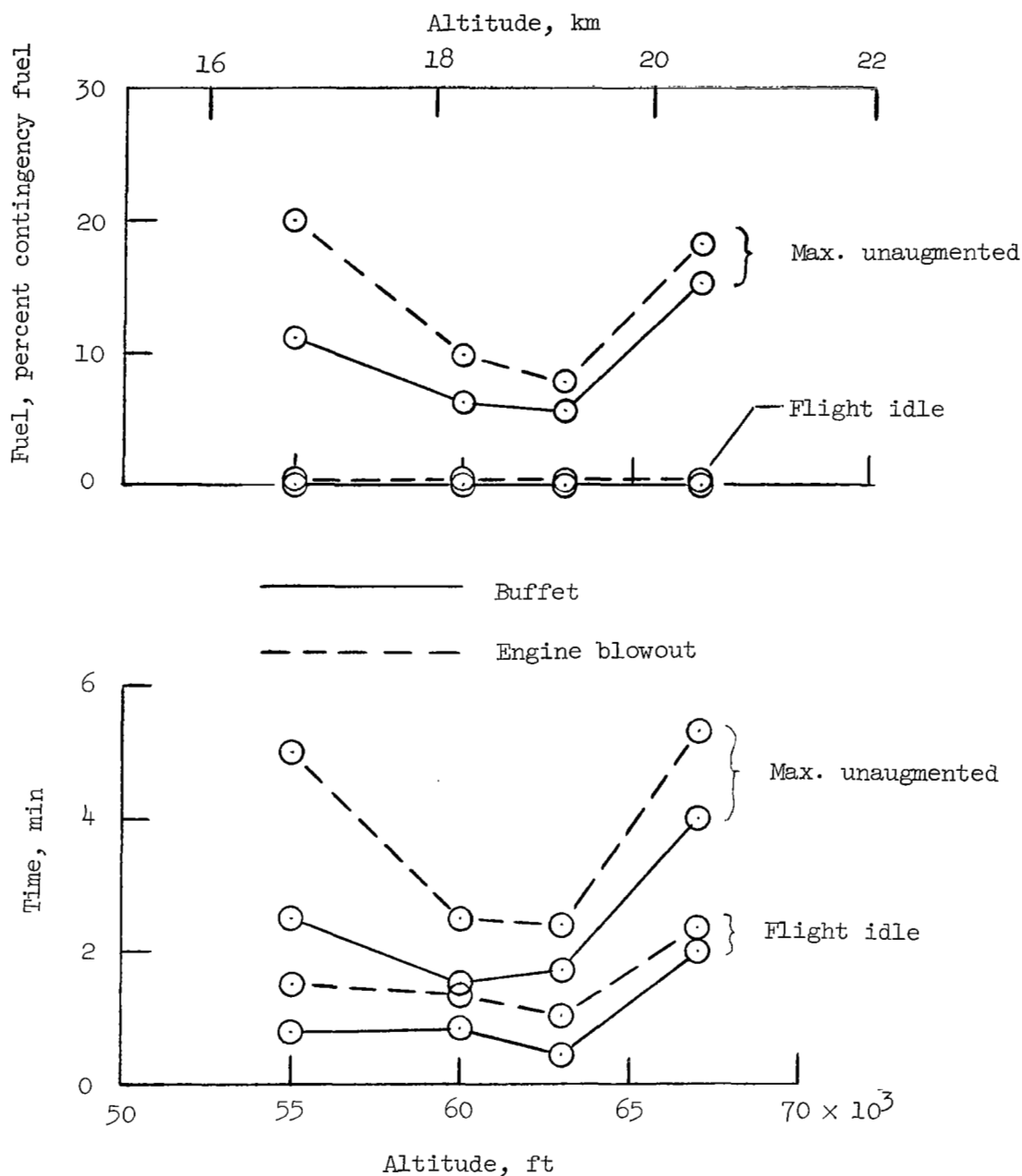


Figure 19.- Elapsed time and fuel use in descent-interrupted operations above the service ceiling between initiation of leveling and penetration of buffet and engine blowout boundaries. SST configuration A. For descent schedule with maximum Δp of 1.5 pounds force per square foot (71.8 N/m²).

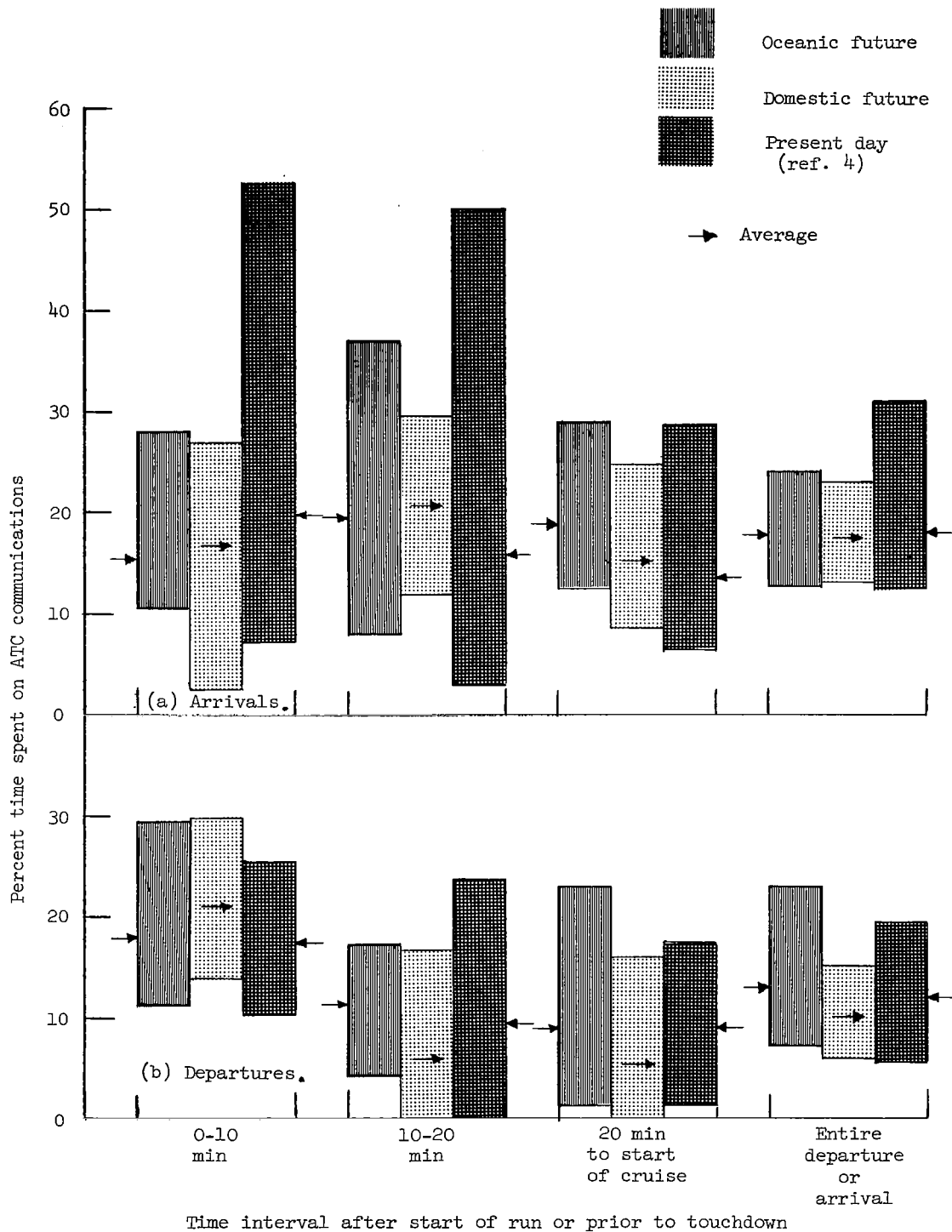


Figure 20.- Percent of time spent on ATC communications. Future and present-day ATC systems. JFK area.

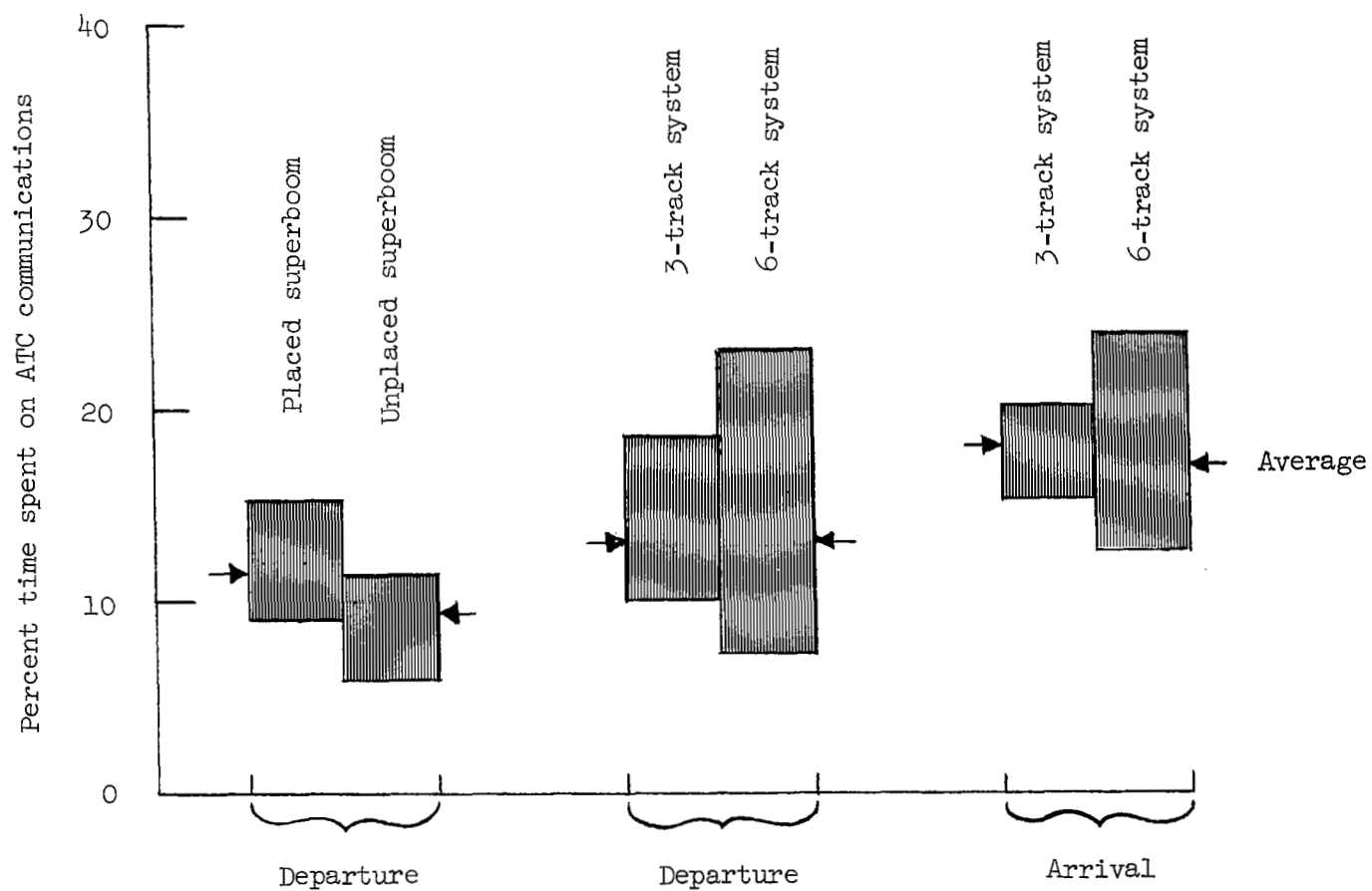
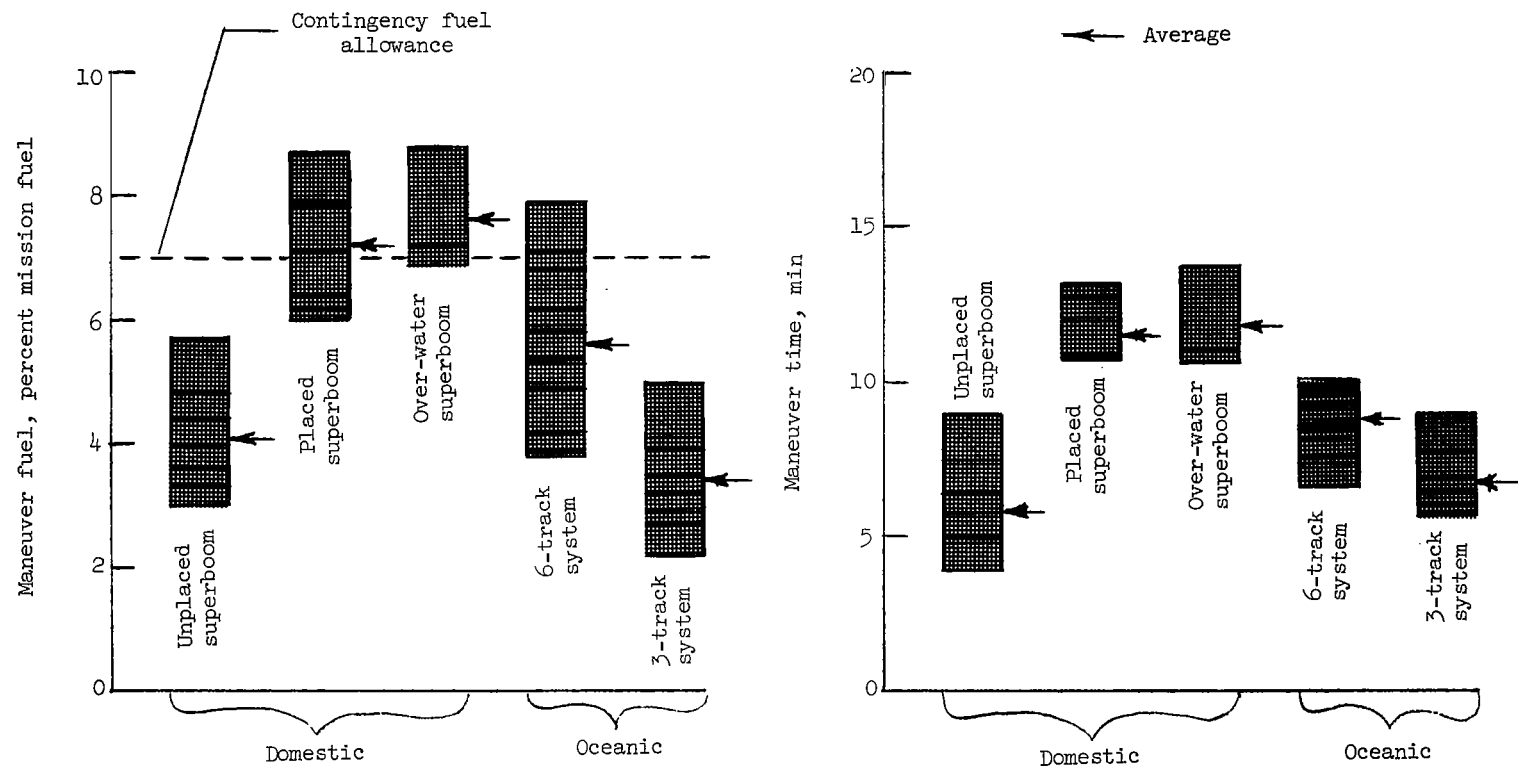
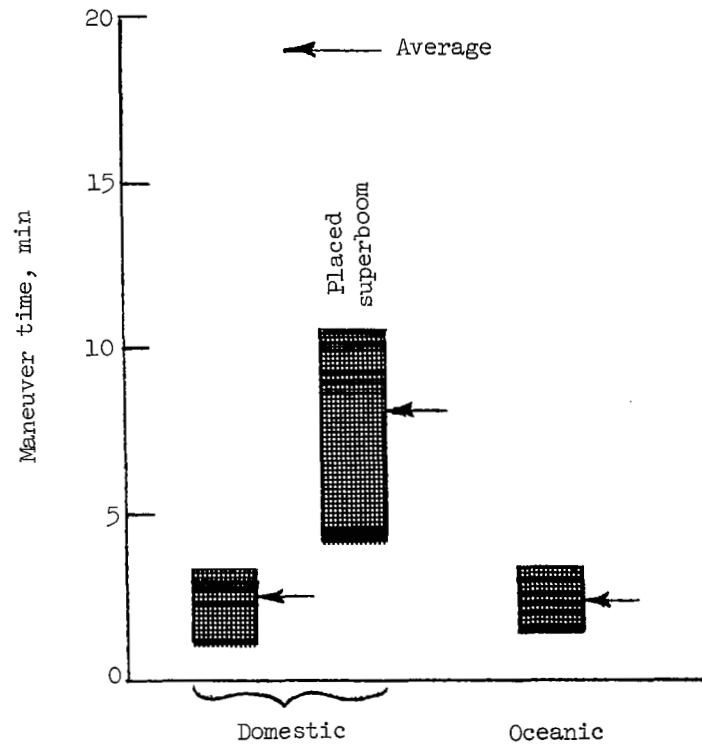
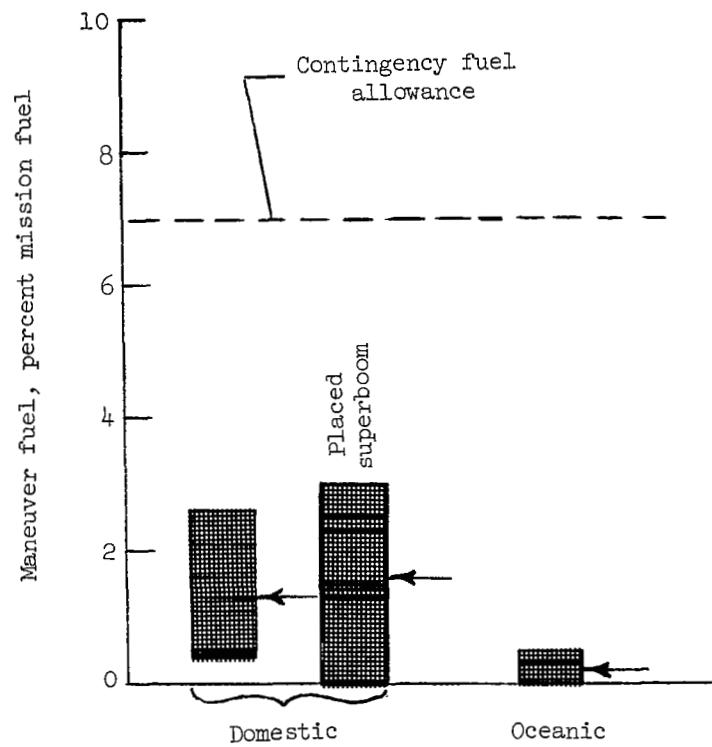


Figure 21.- Comparisons of percent time spent on ATC communications for special and standard operations at JFK. Future ATC system.



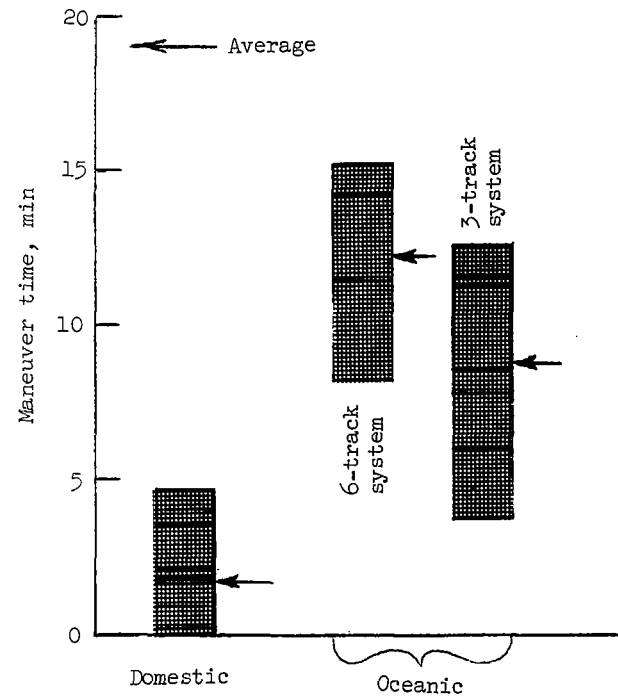
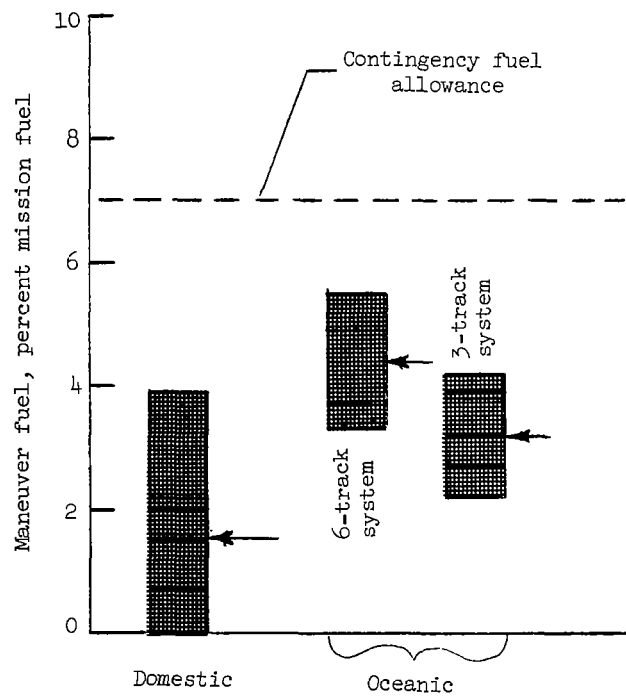
(a) JFK departures.

Figure 22.- Maneuver time and fuel for departure and arrival operations.



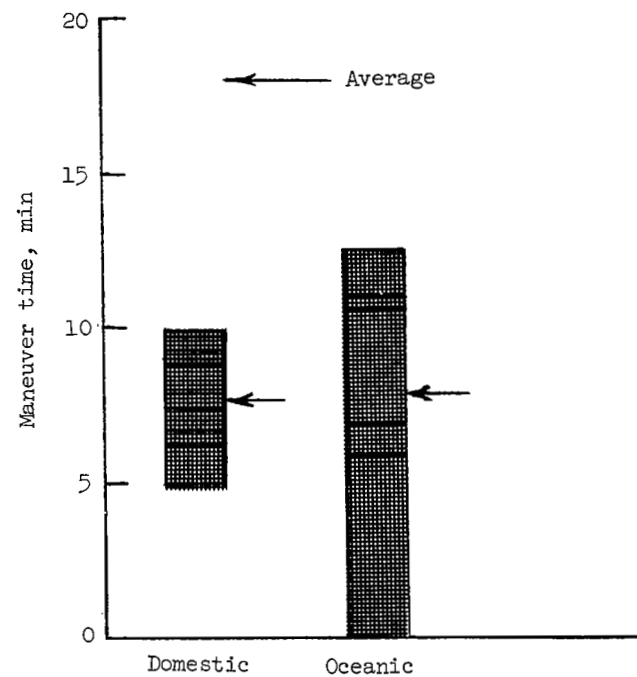
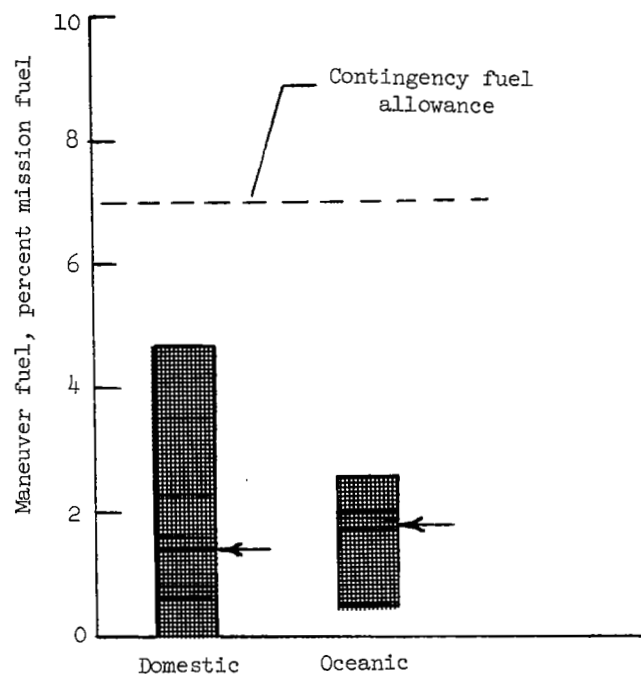
(b) LAX departures.

Figure 22.- Continued.



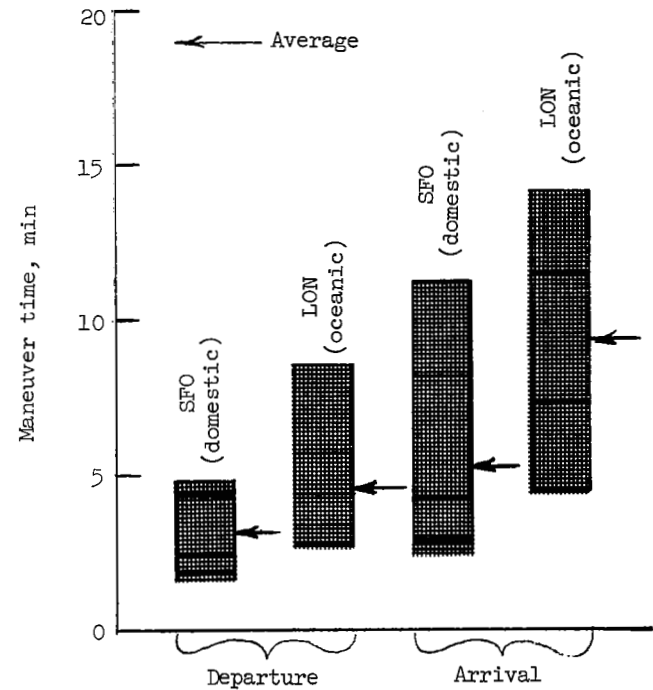
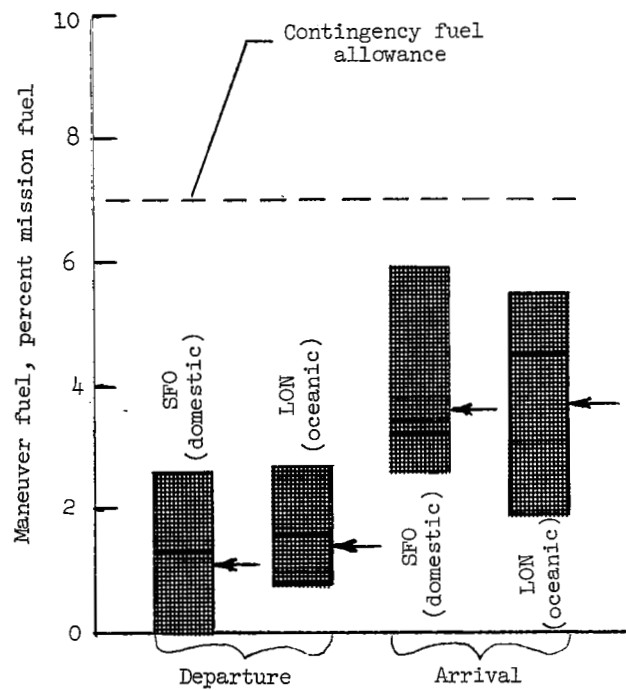
(c) JFK arrivals.

Figure 22.- Continued.



(d) LAX arrivals.

Figure 22.- Continued.



(e) SFO and LON departures and arrivals.

Figure 22.- Concluded.

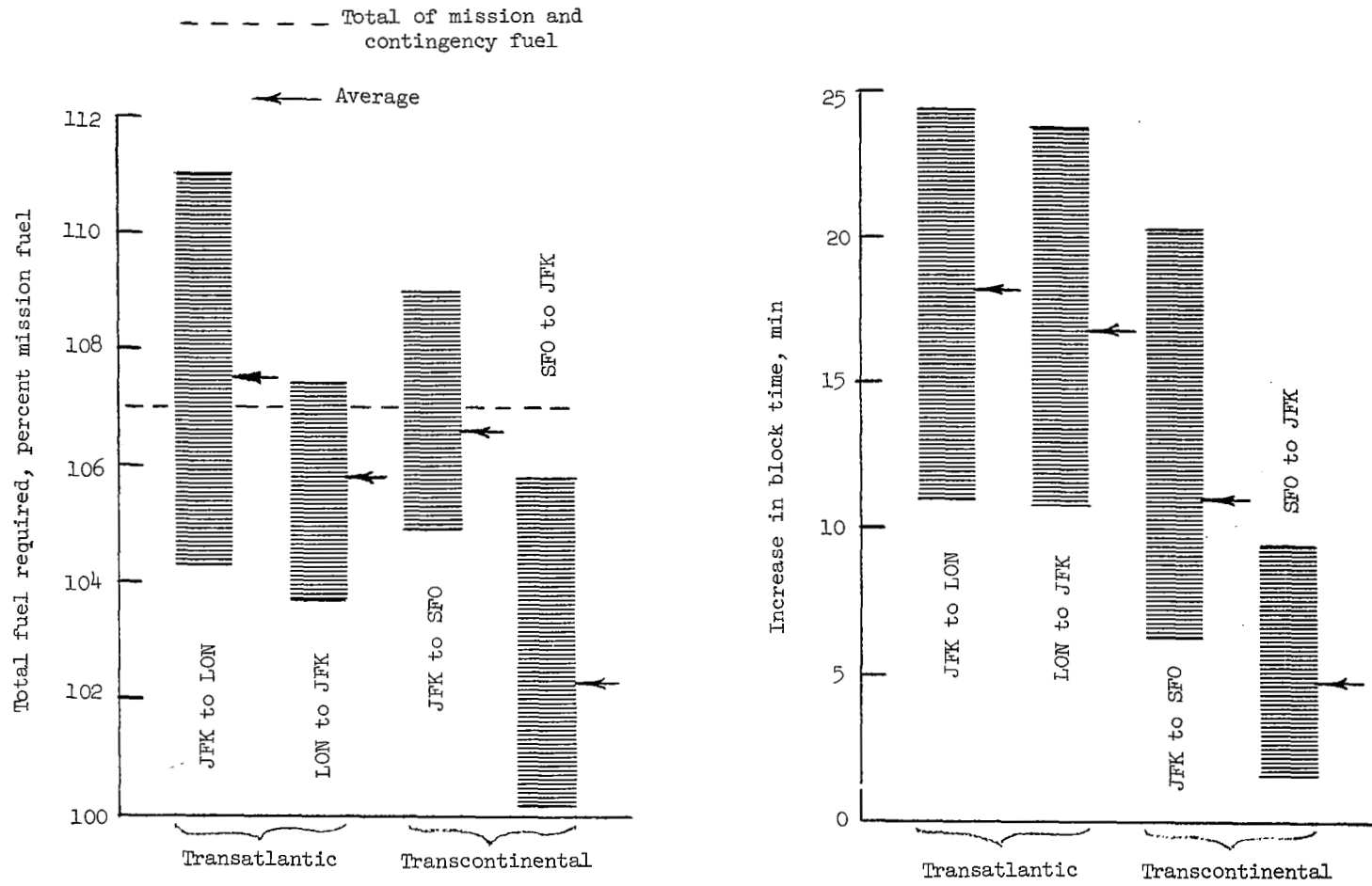


Figure 23.- Effects of operations in future ATC systems on fuel requirements and block times for transatlantic and transcontinental missions. SST configuration B.